# Centrifugal separator diagnosis

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**CENTRIFUGAL SEPARATOR FAULT DIAGNOSTICS**

**MASTER THESIS**

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# DIJAGNOSTIKA CENTRIFUGALNOG SEPARATORA

# CENTRIFUGAL SEPARATOR DIAGNOSIS

## MASTER THESIS

Course: Advanced diagnostics

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Study program: Marine engineering and technology of maritime   transport

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### IZJAVA O SAMOSTALNOJ IZRADI DIPLOMSKOG RADA

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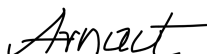
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**SAŽETAK**

Centrifugalni separator je tehnologija koja se koristi za odvajanje dviju tekućina različitih gustoća odnosno pročišćavanje tekućine koja sadrži krute čestice. Dobavni sustav priprema i dovodi neobrađeno ulje/gorivo u separator. Proces odvajanja vrši se unutar bubnja na površini sloga tanjura gdje lakša tekućina izlazi preko unutarnjeg, a voda preko vanjskog ruba, dok se talog zadržava na stijenkama bubnja. U trenutku kada brojač istekne ili kontrolna jedinica registrira vodu u pročišćenom ulju, izbacivanje taloga se ostvari putem hidrauličke jedinice koja se nalazi ispod bubnja. Pogonska jedinica osigurava okretni moment kojim se bubanj rotira, time stvarajući snažno centrifugalno polje unutar bubnja. Kontrolna jedinica bazirana na PLC-u osigurava automatsku operaciju uz konstantno praćenje radnih parametara. Ako njihova vrijednost prijeđe dozvoljenu granicu, alarm se uključuje koji je indikacija potencijalnog kvara. Primjenjujući metode dijagnostike, te uz pomoć sustava detekcije kvarova, časnik stroja može izolirati i otkloniti kvar kako bi vratio separatorski sustav u normalno stanje.

Ključne riječi: alarm, detekcija kvarova, dijagnostika kvarova, centrifugalni separator, dobavni sustav, bubanj, sustav za izbacivanje taloga, pogonski sustav, upravljačka jedinica

**SUMMARY**

Disc stack centrifugal separator is technology used for separating two different density liquids or purifying liquid by removing solid particles that it contains. Feed system prepares and delivers dirty oil to the separator. Separation process takes place within bowl assembly where lighter liquid flows out through the inner and water through outer edge outlet with sludge building up on the bowl side. Once the timer runs out or the control unit detects water in clean liquid outlet, sludge discharge is initiated by means of hydraulic mechanism located beneath the bowl. Power and transmission unit provides torque for bowl rotation so that strong centrifugal field is created. PLC based control unit ensures automatic operation and constantly monitors operation parameters. If their value crosses threshold, alarm is sounded which is indication of potential fault. By applying fault diagnosis methods, and with aid of fault detection system, engine officer can isolate the fault and find remedy so that purification system can be restored to normal operation.

Keywords: alarm, fault detection, fault diagnosis, centrifugal separator, feed system, bowl assembly, sludge discharge mechanism, power and transmission unit, control unit

# CONTENT

# 1. INTRODUCTION

## 1.1. OBJECT OF RESEARCH

Every system that is working under longer periods will inevitably fail. Diagnosing faults and removing them is a dual problem, meaning that first, it demands sufficient knowledge about the system itself and its operation, and second, the knowledge about fault diagnosis techniques and principles. Often identical faults can have different origins. Object of this research is separator with its sub-systems and methods/techniques for fault detection and diagnosis.

## 1.2. WORKING HYPOTESIS

Hypothesis that shall be tested is the following: theoretical knowledge about the separator and its components is indispensable to understand causes, the nature of alarms and failures associated with it.

## 1.3. PURPOSE AND AIM OF RESEARCH

Purpose and aim of this research is to give overview of fault detection and diagnosis methods, describe centrifugal separator in terms of its elements and operational parameters and finally, understand causalities that produced alarms and faults.

## 1.4. SCIENTIFIC METHODS AND THESIS STRUCTURE

During research, formulation, and presentation of results of research, following scientific methods were used in appropriate combination. Classification method was used in chapter 2 to present overall methods and techniques in fault detection and diagnosis. Basic terminology and ideas related to the field are introduced.

Historical method was used in chapter 3 and as introduction to chapter 4, to give historical context of the development of centrifugal separator. Also, separation process as a physical phenomenon is explained by comparing gravitational and centrifugal separation.

In chapters 4 analysis method was used to break down centrifugal separator into its main sub-systems in order to give full interpretation of device operation and the roles of every sub-system. In chapter 5 modern separation technologies are described

The last chapter deals with alarms and failures that can occur during separator operation. It is a synthesis of all previous chapters since they are necessary for understanding origins of faults.

# 2. INTRODUCTION TO FAULT DIAGNOSIS

Fault diagnosis is a procedure that is always considered when observing a device, machine, or a system under longer periods of operation. From empirical observations comes the conclusion that occurrence of a fault decreases the performance, reliability, and safe operation of a system. Furthermore, if the fault isn't detected in early stages it will lead into failure or malfunction. When considering production systems such as factories, etc. such events cause both direct and indirect expenses, with former resulting from spare parts and services required to perform replacement and latter from inability to produce and therefore achieve profits. By means of sophisticated detection systems and regular maintenance schedules unexpected events which can temporarily stop production can be avoided

In the context of centrifugal separator and depending on the severity of fault, the separator operation can be stopped and one inspected. The information about malfunctioning state and respective faults of purifying system is detected via built-in system which constantly monitors its operating parameters (e.g., fuel temperature and electrical resistance). Moreover, by means of alarm the information reaches engine room crew to which they respond. Because purifying system is redundant, systems robustness is increased. Different separator can be put into operation while task of fault diagnosis is carried out by the engineering officer. After the engineering officer finishes troubleshooting and detects the fault/malfunction/failure, he can determine the scope of repairing task, necessary tools and spare parts required.

Purpose of this chapter is to give overview of most used techniques for fault detection and diagnosis. This will be achieved by emphasizing few key features and context in which their application yields best result.

## 2.1. BASIC TERMINOLOGY

Before diving into various aspects of this chapter one should consider following definitions. According to [1] „A <u>fault</u> is an unpermitted deviation of at least one characteristic property (feature) of the system from the acceptable, usual, standard condition ". By its nature it is a state within the system which may initiate a failure or malfunction. Also, it could be the case that a fault does not affect the correct functioning of a system. Frequently, faults are hard to detect, due to their location and size (small or hidden).

<u>Fault detection</u> is a first step in the process of returning the systems state into normal operation. By using dependencies between different measured signals fault can be detected thereby generating symptoms which are necessary for fault isolation and its analysis.

In order to successfully complete the task, system must be able to acquire data through sensors, process it by means of algorithms so that data produced can be used as fault indication to the engineering officer. Before the implementation of automated systems most common way to detect deviations in normal operation was to use biological senses. By observing, touching, listening, and smelling, irregularities in system/machine operation could be detected and responded to. Symptoms produced this way are of qualitative character and are called *heuristic*.

Heuristic information is expressed as linguistic variable (e.g., cold/hot, large/small) or as vague number (e.g., around 50) This approach is limited, but useful and still used in practise today. Later, as technology had developed, essential functions such as: monitoring, automatic protection and supervision with fault diagnosis became basic characteristic of every automated system[1]. In contrast to heuristic symptoms, *analytical* symptoms are detected via sensors, possess precise value, and are used in mathematical models for fault detection. Third group belongs to *statistical* symptoms which are known as empirical data (frequency of faults, time without fault, fault duration) for specific device or system [2],[3]
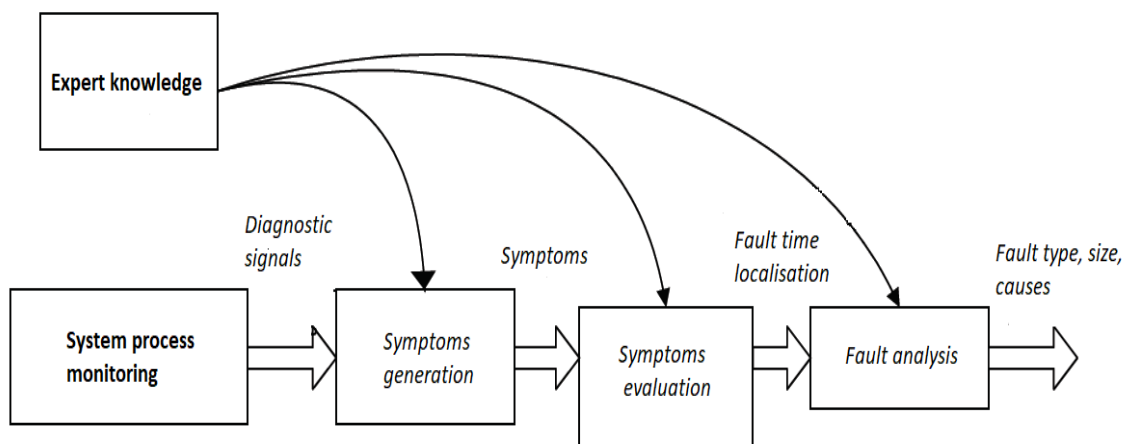
*Figure 1. Fault diagnosis procedure [3][2]*

After a fault has been detected a process of <u>fault isolation</u> takes place by determining the size, location, and type of fault by using heuristic and analytical symptoms and applying knowledge and experience.

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[1] Systems for fault detection are in number of ways far superior then human, especially when considering large complex systems.

[2] Depending on the type of industry or area where fault diagnosis is applied, steps for its successful implementation can differ but they share common properties.

This step yields additional useful information which help in solving fault. When it has been located, fault analysis can be performed. It is successful when the root cause of fault has been understood and its remedy found.[3]

„A failure is a permanent interruption of a system's ability to perform a required function under specified operating conditions. "It results from one or more faults. Based on number single and multiple failures can be distinguished.

With regards to *predictability,* there are random failures which are unpredictable, or in other words they are statistically independent from operation time or other failures. Also, there are predictable failures for certain conditions called deterministic failures and systematic/causal failures which are dependent on known conditions. Latter ones occur only after the operation of device/component had already begun with large stresses that act inside the system over accepted limit.

„A malfunction is an intermittent irregularity which impedes system in performing its desired function. "It is as a temporary interruption of a system performance. Just as failures, malfunctions are events. When the system is operating in a stressful environment chances for malfunction proportionally increases. In all cases it results from one or more faults.

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[3] Note: Fault diagnosis has the same principles as failure diagnosis so the difference in the terms is not relevant in a manner that the same principles cannot be applied to both.

The way in which failure and malfunction develop and differentiate is shown on the figure 2 on following page.
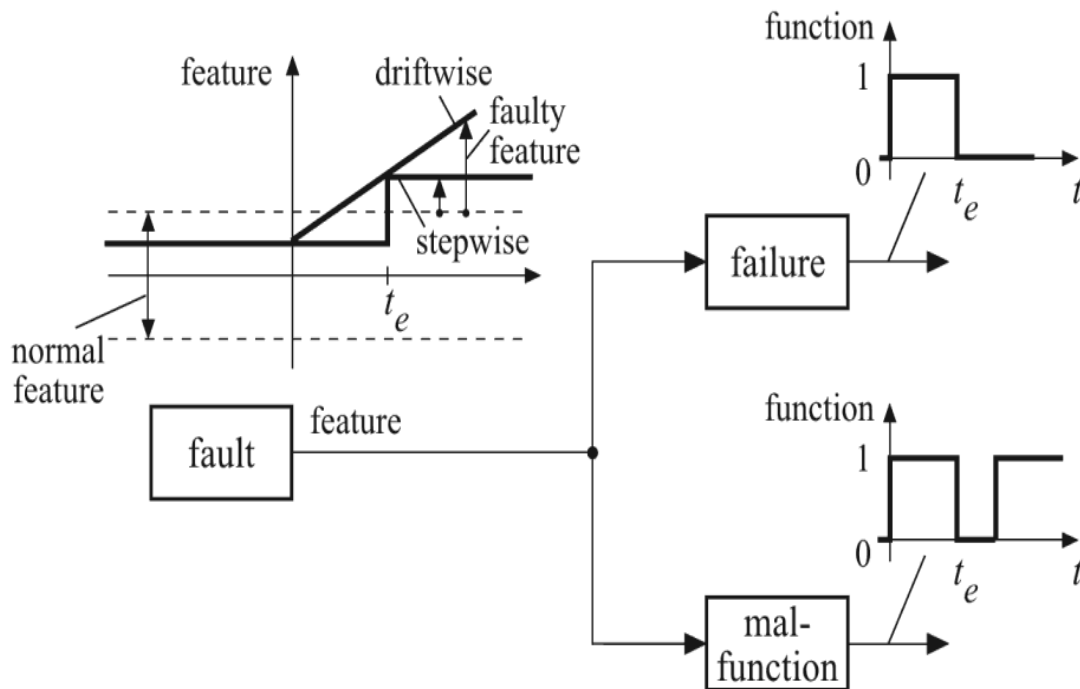


*Figure 2. Development of events „failure "and „malfunction "[1]*

Another set of terms which offer perspective on systems operation regarding unwanted events are as follow.

Reliability – „Ability of a system to perform a required function under stated conditions, within a given scope, during a given period. "It is a physical value which is a function of time. It is affected by malfunctions and failures. Unit in which is measured is the Mean Time to Failure (MTTF) which is the average time needed for product to fail. It is inversely proportional to lambda ($\lambda$) defined as the rate of failures per time unit.

Diagram which is used to visually present reliability of some product is called "Bathtub curve". It is a distribution of overall product failures with respect to age of a product (time under operation) in the moment of failure. It is taken from a large sample (for example 1000 or 10000 products). It consists of three zones where failures are classified according to their failing rate and time.
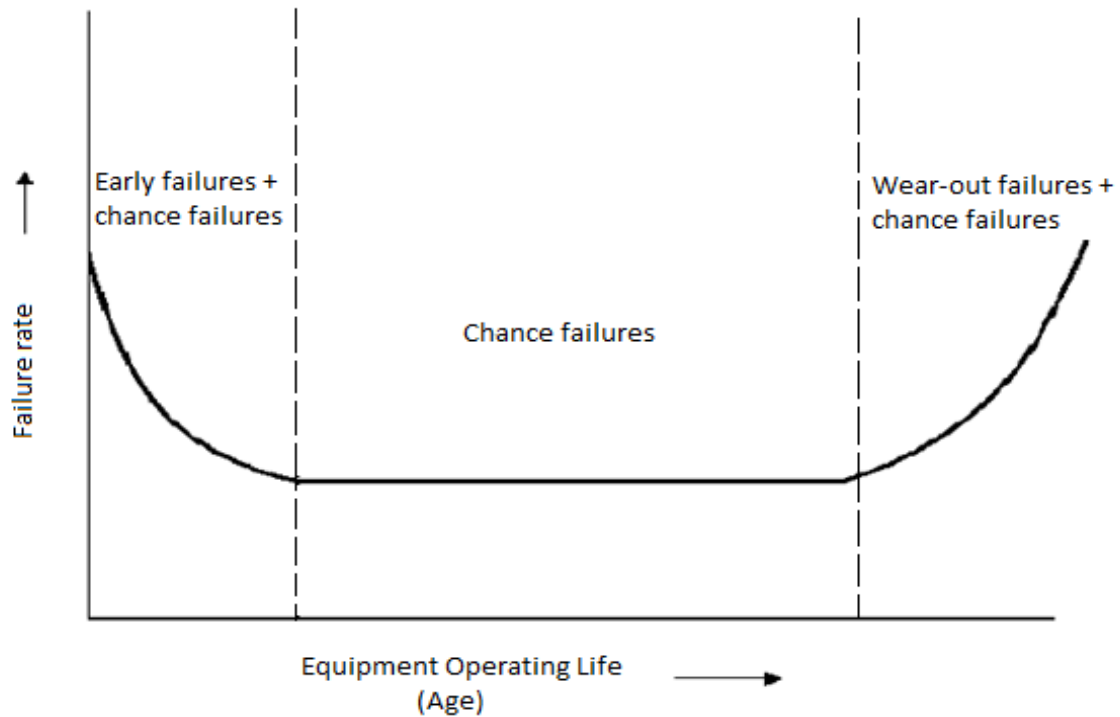
*Figure 3. Bathtub curve depicting reliability in terms of failure rate of equipment [4]*

First part of the curve is characterised by high failure rates with decreasing slope ($d/d_x < 0$) and is colloquially termed „infant mortality ". These failures are highly unwanted and are detected via trial run and during "running in" period of a product. Their origin is explained by material irregulates, errors in design or assembly, just to name a few.

Normal failures are in the middle of the graph, also termed „chance failures". In theory these failures occur randomly with failure rate change being $d/d_x = 0$ when measured over longer time interval. Reason a device failed is attributed to inequal distribution of stress and strength.

After some time, products begin to fail in increasing fashion which is shown in the last part of the graph with increasing failure rate ($d/d_x > 0$). Reason for this lies in unavoidable material wear and fatigue. While designing a product, engineers must satisfy condition that shortest lived component needs to last long enough to provide useful service life. It is also important to note that the information about point in time when a product will fail, cannot be derived from this graph.

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Depending on the quality, type and application of the products, failure rate decrease can be still observed after few years of product service while on the other hand increasing failure rate (last section of the graph) can even be observed after just few months of products service.

Safety – „Ability of a system to not cause danger to persons or equipment or the environment." Its concern lies in the dangerous effects which faults, failures and malfunctions possess. A relation between the reliability and safety exists.

If reliability of a system is improved, it will generally improve safety also. However sometimes an improvement of safety can result in a deterioration of the reliability because, for example, the number of components increases. In order to achieve safety and reliability following tasks must be insured: fault avoidance, fault removal, fault tolerance, fault detection and diagnosis, automatic supervision, and protection.

Availability – „Probability that a system or equipment will operate satisfactorily and effectively at any period. "This is important aspect when considering all possible systems state changes and their results. If within the system specific elements are coupled in certain way, then overall state of a system is dependent upon availability of specific elements. It also considers that failures and malfunctions happen and need some time to repair.

Integrity – „ The integrity of a system is the ability to detect faults in its own operation and to inform a human operator. "This is important characteristic of a system which points to the relation between built in detection system within the observed device/system and the human operator as an outside element with whom the information is shared. The direction of information exchange goes into both directions where upon receiving information, human operator, for example engineer, will have adequate response to the system where fault is detected.[1],[4],[5],[6]

**2.2 FAULT CLASSIFICATION**

As previously shown in section 2.1.1. under definition of reliability, faults can be classified by the failure rate as a function of time (Bathtub curve). Further classification based on some other factors is shown in following figure.
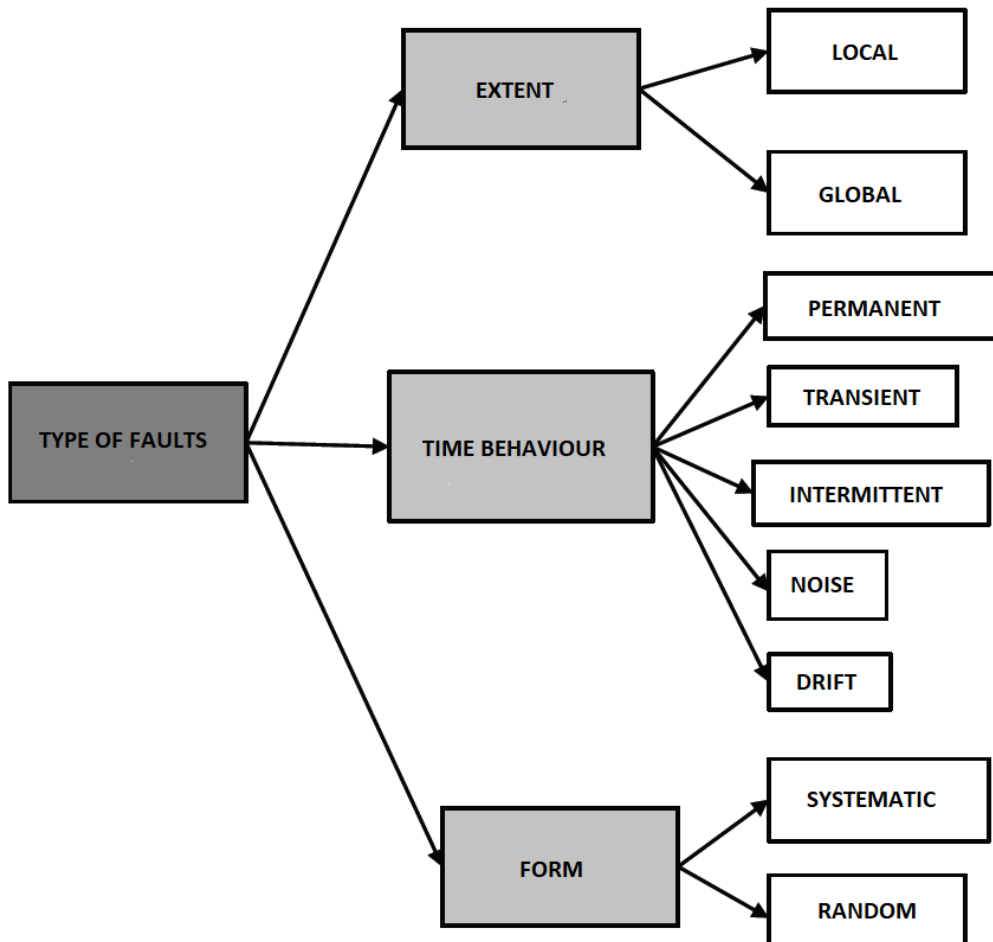


*Figure 4. Types of faults [3]*

Faults can be local or global, depending on size. If observed system is large enough to contain many sub-systems within itself, then appearance of fault on small scale of sub-system is considered „local ". In contrast, detection of fault which affected observed system not only on large scale but also systems environment is termed as „global ".

Second group is classified upon time behaviour of the fault. Permanent faults will continue to exist until the task of repairing has been taken. Their appearance is sudden with permanent change of either physical parameter or systems structure. The difference between transient and intermittent faults lies in the ability of determining the frequency at which they occur with former having unknown and latter known/characterised frequency.

Faults with drift-like nature evolve slowly over longer period and get detected only when the threshold level is achieved. Noise is disturbance which occurs in the process of signal transmittance and detection.

Finally, there is difference in form which faults may have. Systematic faults arise from human errors while developing or operating the system. Each step in the systems life i.e., from specification and design to maintenance and decommissioning is exposed to risk of systematic fault. It will always appear when triggered by circumstances, until it is removed. On the other side, random faults occur due to physical causes and are related mostly to hardware components. They will manifest themselves under conditions like corrosion, thermal and physical stressing and naturally occurring wear-out. By gathering large amounts of data about random faults for some system/device, probability functions can be derived thus predicting occurrence of such faults. [7]

### 2.3. FAULT DETECTION METHODS

Today fault detection systems play major role in every automated system due to their importance of detecting faults early so that a downtime or decline in performance can be avoided. Many methods for fault detection exist based on different approaches.

#### 2.3.1. Data methods and signal models

Data driven methods used for fault detection are based on available historical (experimental data). These methods present an alternative way for large-scale facilities since model-based systems would require too much effort.

##### 2.3.1.1 Limit and Trend Checking

Two limit values $Y_{min}$ and $Y_{max}$ present boundaries with normal state $Y(t)$. Fault is detected when $Y(t)<Y_{min}$ or $Y(t)>Y_{max}$. If the first derivatives of states are used for comparison, then the method is called Trend Checking. Although practical and reliable the response is rather slow, occurring only when large change of feature is in question.

##### 2.3.1.2 Principal Component Analysis

This method is convenient for application when large data set is in question. By reducing dimensionality and applying transformation, big number of interrelated variables ($m$) becomes new set of variables named *principal components* which are uncorrelated contrary to variables measured in real system or recorded in historical data. Then a considerably smaller set of variables ($r$) is searched.

These contain most of the information about the variance and covariance between $m$ variables which was of interest in first place.
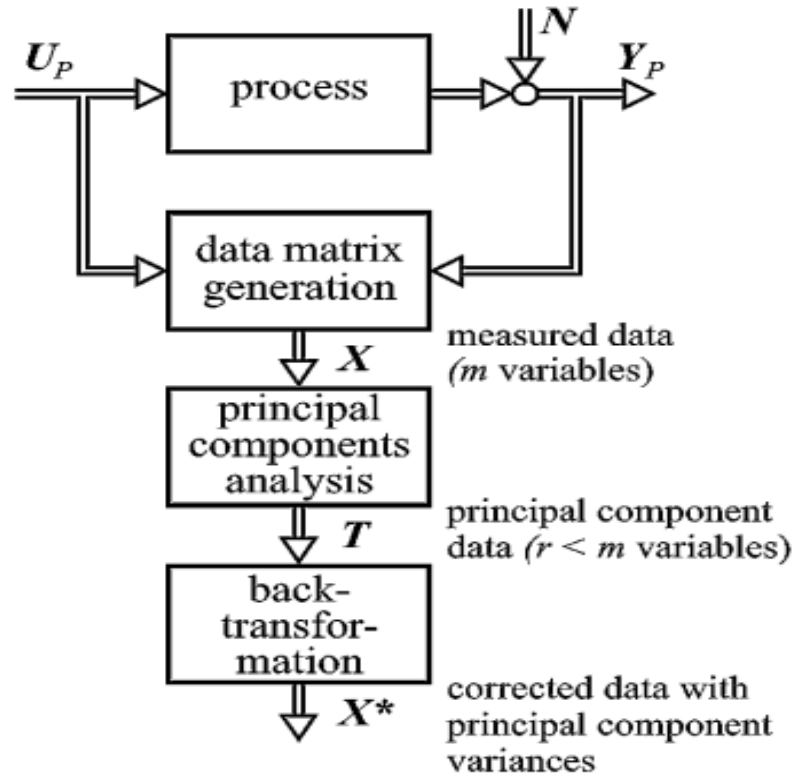
*Picture 5. Principle Component Analysis [8*]

By building orthogonal vectors from *r* number of variables ordered so that the first few contain most of the data variation, principal components are formed which are practical and sufficient for use and display of data variance. [8]

*2.3.1.3 Spectrum analysis and parametric models*

This method can be applied if it is possible to make relation between change in the signal and a process fault. By means of mathematical models used for signal analysis a suitable feature (e.g., phases, amplitudes and spectrum) can be calculated. A comparison between normal behaviour and observed features yields analytical symptoms.
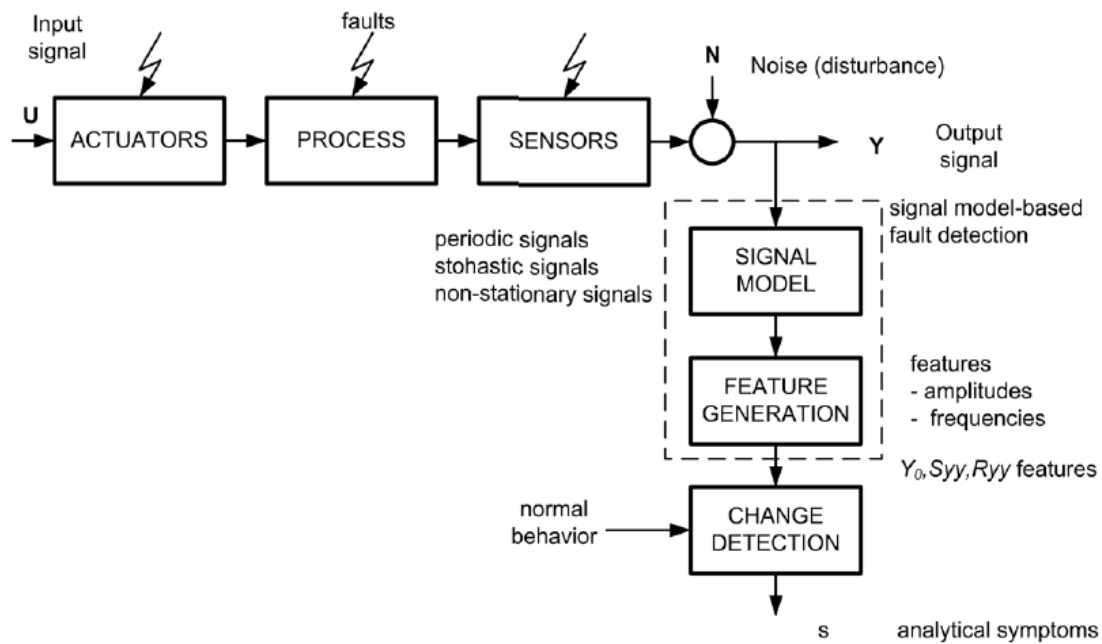
*Figure 6. Fault detection with signal models* [8]

Last group of data driven methods for fault detection uses algorithms for pattern recognition. These techniques do not contain explicit modelling of internal states of process, rather an association between data patterns and fault types is established thereby detecting a fault.[8]

### 2.3.1.4 Neural Networks

Their structure and the way they operate is greatly inspired by the architecture of the mammalian brain. Basic unit of such system is also called neuron, a single processing element whose purpose is to hold certain value and activate once their input exceeds certain threshold. These are then ordered in layers with first layer being fed by training data. Based on given data inputs and the weights plus biases associated with each connection between neurons in first layer and the hidden ones (layers in between), neural network gives output in the last layer. Necessary step in using neural networks is training process. It is accomplished by feeding data and correcting on mistakes it made when giving wrong outputs. If applied to the tasks of fault detection, neural network is fed by input-output pairs with both normal and faulty conditions. So far neural networks have demonstrated huge potential for practical application in fault detection. Besides latter, they are also applied in fault diagnosis, machine learning etc. On the following figure neural network with backpropagation algorithm is presented.[8] [9]
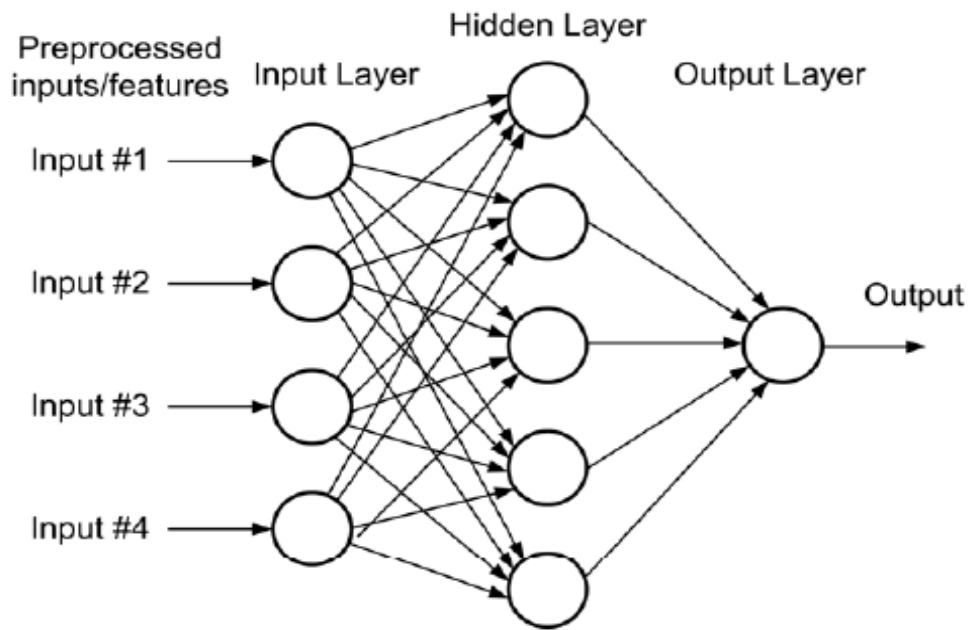
*Figure 7. Structure of feedforward neural network [8]*

### 2.3.2. Process Model-Based Methods

On the following figure, general scheme for process model-based fault detection is shown.
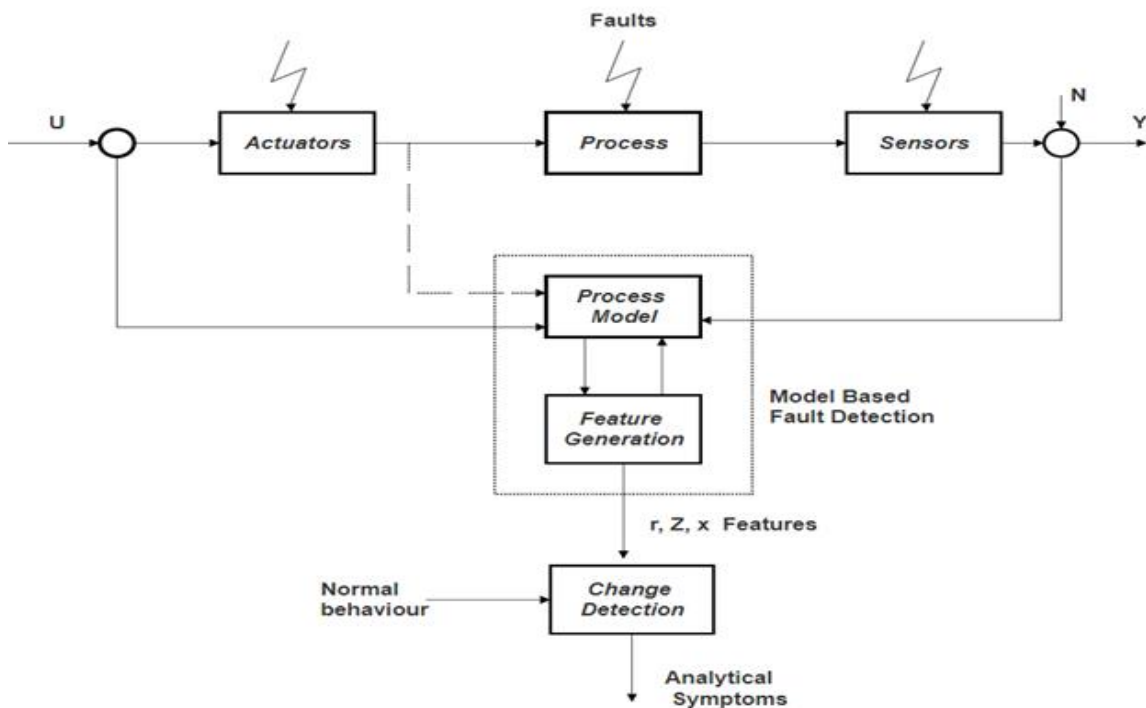


*Figure 8. Process model-based fault detection [8]*

Faults can occur on system actuators and sensors as well as in the process which is carried out by the system in question. First step involves measuring the input signal U and output signal Y of the real, physical system. Besides the latter, a non-physical analytical mathematical model is installed which is simulating operation of a system based on input parameters. Model is described by the system of differential equations, and solutions of those equations are the output of process model. By assuming that the model is almost 100% correct, outputs of the two systems can be compared. Results gained are called *features* where *r* is residual, *Z* parameter estimate and *x* state estimate. The change between observed features and nominal values generates analytical symptoms which can be later used in fault diagnostics. [8]

### 2.3.2.1. Parity equations

Real process is described by transfer function $G_p(s)$ and the analytical model with $G_m(s)$. When the values of two transfer functions are subtracted the residual *r'* i.e. output error is gained thus fault can be detected. Principle is captured in the following figure.
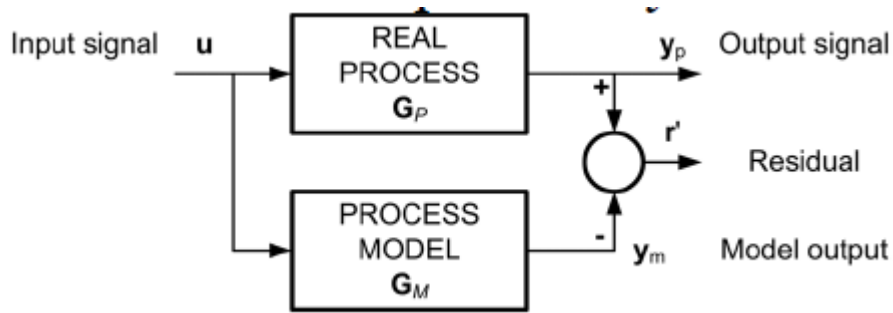


*Figure 9. Model-based fault detection using parity equations [8]*

### 2.3.2.2. State observers

Another method for calculating residual *r* is by means of state observers. State variable changes ($\Delta x_i$) become models of faults. Complete system description is carried out in state space representation form:

$$\dot{\hat{\mathbf{x}}}(t) = \mathbf{A}\hat{\mathbf{x}}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{H}\mathbf{e}(t)$$

$$\hat{\mathbf{y}} = \mathbf{C}\hat{\mathbf{x}}$$

$$\mathbf{e}(t) = \mathbf{y}(t) - C\hat{\mathbf{x}}(t)$$

$$\mathbf{r}(t) = \mathbf{W}\mathbf{e}(t)$$

This method was originally developed by control engineer Rudolf Emil Kalman during 1960-ies. Input signal is both fed to the process and analytical model.

The real system (process) depending on its complexity always differs from analytical model (due to non-linearities, non-modellable friction etc.) For that reason, gain matrix W is implemented to nullify those differences as much as possible. In the same manner as with other approaches, residual $r$ is gained by subtracting output signal from real system and the one from analytical model. All relations between the state observers are shown in block diagram format on following figure.[73]
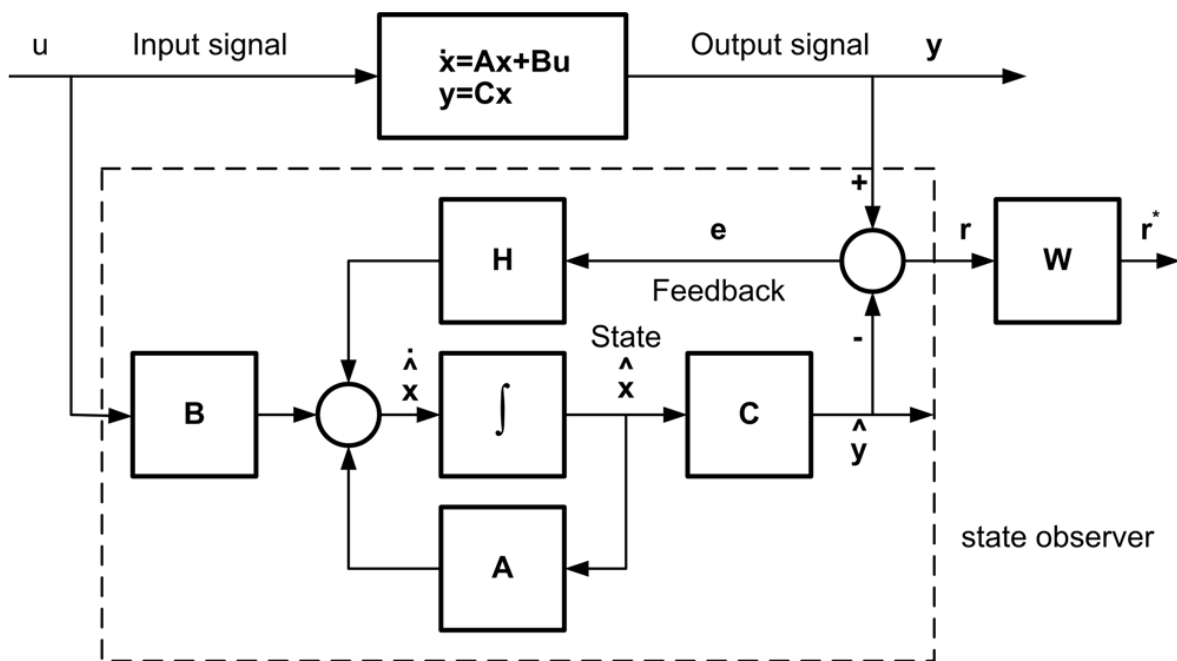


*Figure 10. Fault detection with state observers [73]*

### 2.3.2.3. Parameter estimation

If the process parameters are partially known or in the worst case - not known at all, they can be determined by means of parameter estimation method for fault detection. Because the structure of basic model is known, inputs and outputs can be measured thus identifying systems parameters. Those can be used to derive faults of dynamical system by means of following procedure:

1. Parameters which describe the model of a system must be chosen

2. Relationship between physical parameters $p_i$ and model parameters $\Theta_i$ is determined; $\Theta = f(\mathbf{p})$

3. From inputs and outputs of real system model parameter vector $\mathbf{\Theta}$ is created

4. Parameter vector $\mathbf{p}$ is gained as a function of model parameters; $\mathbf{p} = f^{-1}(\Theta)$

5. Vector deviations $\Delta\mathbf{p}$ are calculated as a difference between nominal and real values

6. Because of their relationship, faults can be determined from changes in physical parameters, $\Delta p_i$

Block diagram of this type of process model-based fault detection method is shown in figure 12 on following page.[8]
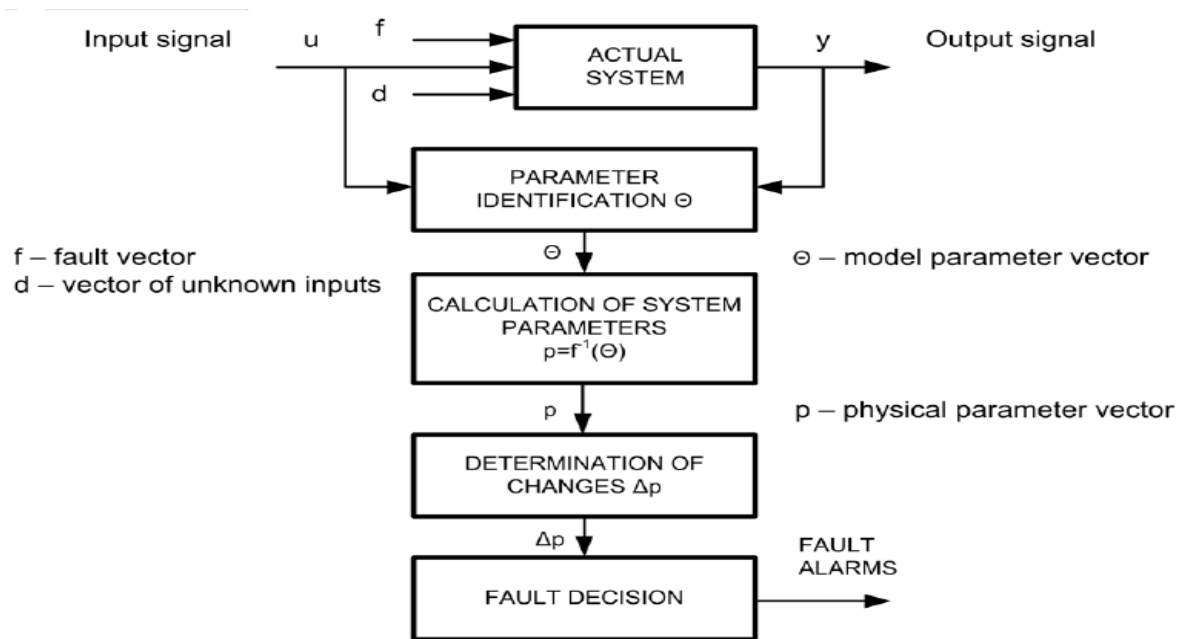


Figure 11. Fault detection with parameter estimation [8]

### 2.3.2.4. Nonlinear models

Sometimes systems in question are too complex for conventional modelling approaches. Furthermore, issues such as lack of precise formal knowledge and nonlinearity demand more sophisticated ways in building models. Again, neural networks have proven to be powerful tool when dealing with systems with strong non-linearities where physical model structure is unknown or partially known. One of the disadvantages lies in inability to directly interpret non-linear model. However, after reference models have been developed, by means of parity equations i.e., analytical redundancy between measured and modelled outputs, residuals are generated which are transparent and interpretable therefore convenient for fault detection.[8]
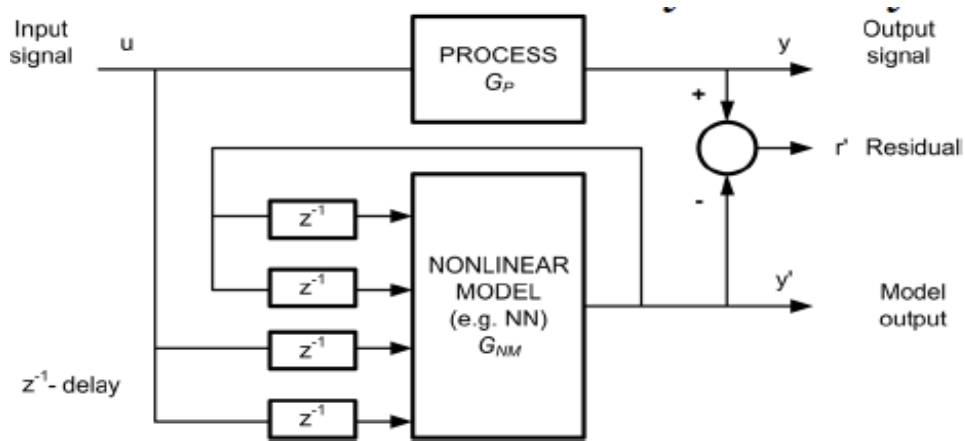
*Figure 12. Fault detection using nonlinear model and parity equations [8]*

### 2.3.3. Knowledge based methods

When dealing with large scale complex systems detailed quantitative mathematical model is not available because it is too expensive or too time-consuming to build. Instead, alternative approaches are: qualitative models obtained through expert knowledge and casual modelling of fault-symptom relationships.

#### 2.3.3.1. Expert system

According to Feigenbaum (1982) „expert system is an intelligent computer program that uses knowledge and inference procedures to solve problems that are difficult enough to require significant human expertise for their solution. "It mimics human reasoning with great emphasis on expert's problem-solving abilities and performance of relevant tasks in the manner as an expert does. First were developed rule-based expert systems with later emergence of model-based.
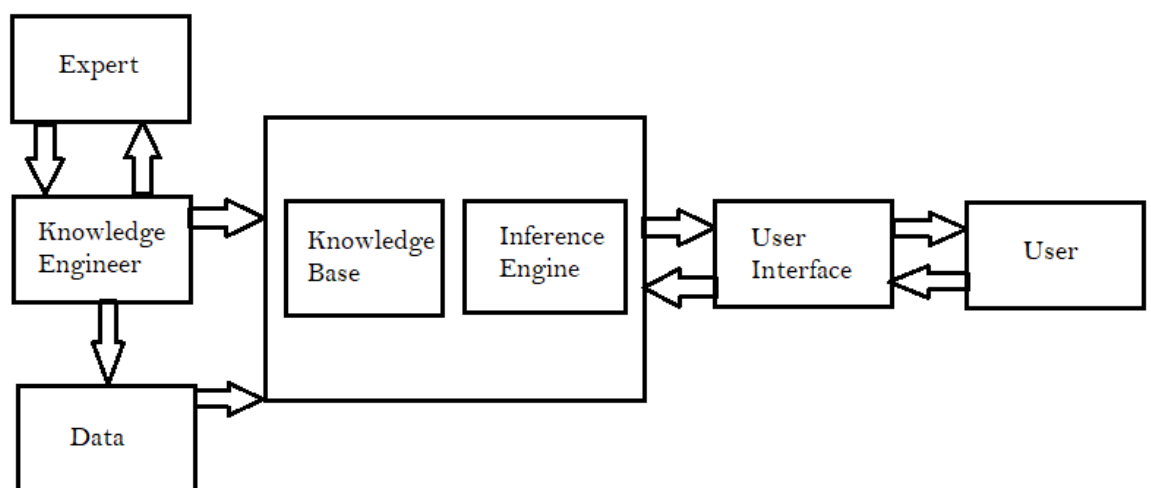


*Figure 13. Basic structure of a rule-based expert system [8]*

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When designing expert system knowledge acquisition becomes one of the biggest difficulties. Experience of domain specialists and operators of the plant is used as main knowledge source. Advantages of such systems are: ability to add or remove rules simply and easier induction and deduction process, but on the other hand its disadvantages lie in: lacking of generality, trouble with handling novel situations, inability to represent time-varying phenomena and costly maintenance. [8],[10]

## 2.4. FAULT DIAGNOSIS METHODS

Once the symptoms in the monitored system are detected it is necessary to analyse them using fault relevant process knowledge so that faults with their properties (e.g. size and location) can be determined. Depending on type and availability of a-priori knowledge two different methods can be employed, with the third being combination of the two. Classification methods find their application if there exists experimental data which describes how symptoms influence fault. On the other hand, if the rules or expert knowledge are used to determine relationships between symptoms and faults, then application of inference methods is effective. If both are applicable to the situation in question, then their combination will yield best results. [11]

### 2.4.1. Classification methods

Development of fault to the point at which can be noticed by related symptoms in general follows cause – effect relationship. Connection between physical properties and variables exists quantitatively and as a function of time. Analytical form of physical laws which describe their relation is often unknown, or too complicated to calculate. Therefore information about its causality is not available and stands in a way of fault diagnosis. The solution to that problem is found by applying experimentally trained classification methods also known as *pattern recognition algorithms*.
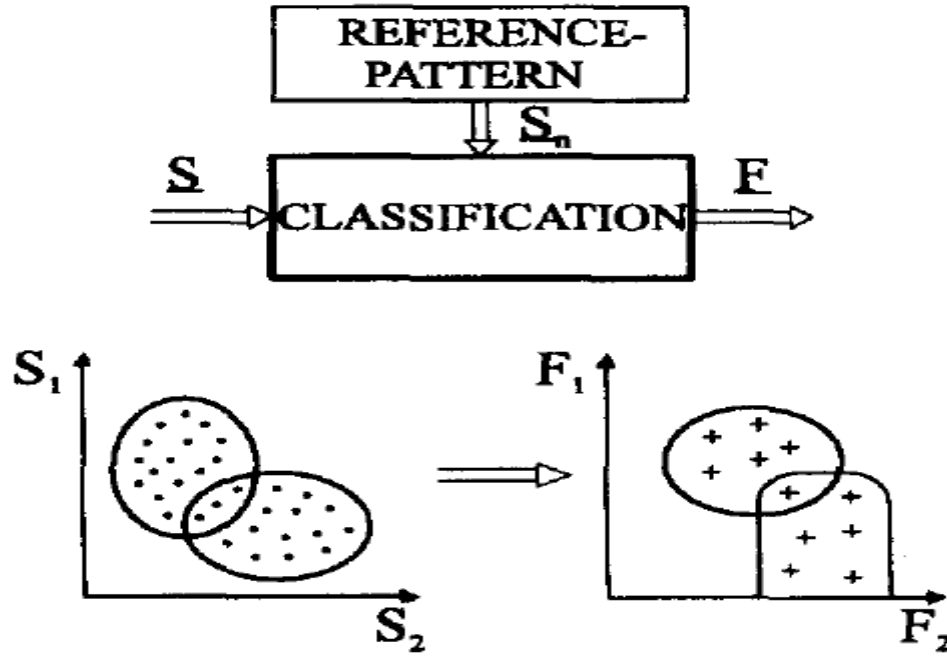
*Figure 14. Principle of classification methods [12]*

Analytic and heuristic symptoms *S* produced by fault detection system can be represented in a feature vector: $S^T = [S_1, S_2, …, S_n]$. In the same manner corresponding faults are presented: $F^T = [F_1, F_2, …, Fm]$. Faults possess binary values with 0 meaning fault did not happen and 1 meaning fault happen.

Normal behaviour of the system is determined by reference vectors $S_n$. By conducting an experiment each input vector S of the feature can be mapped to certain faults $F_j$. In this way relationship between F and S is learned (trained) and thus explicit knowledge base is formed and built into diagnostics system. When the symptom which arises is compared with the referenced one, fault is deduced and thus evaluated. Three most common classification methods are: statistical, geometrical, and polynomial [12]

*2.4.1.1. Statistical classifier (Bayesian)*

This group of algorithms uses certain assumptions about fault symptoms statistics with most notable example being Bayes classifier. By approaching classification problems in probabilistic terms, the Bayesian decision theory is used to determine faults given a set of symptoms.

Let $F_j$ stand for fault *j*. Then *P(Fj)* expresses the prior probability of fault *j* meaning the probability that fault *j* will occur before any symptoms are considered.

Indispensable element from which prior probabilities for all possible faults are calculated is the historical data set of the system in question.

Using only prior probabilities for fault estimation results in low reliability which can be significally increased if available set of measured symptoms **s** is incorporated. Class conditional probability density function for a set of symptoms that belong to fault class $F(j)$ is denoted as $p(\mathbf{s}|F_j)$. It represents the probability distribution of symptom **s** given that the fault $F_j$ occurs. Assuming that prior probabilities are unknown or equal, fault class $j$ for which $p(\mathbf{s}|F_j)$ gives a higher value are more "likely" to be true.

On the following figure an arbitrary distribution of symptom values are depicted with its class conditional density functions $p(\mathbf{s}|F_j)$. Through the point where two functions intersect, vertical line is drawn which represents theoretical decision boundary for faults 1 and 2.
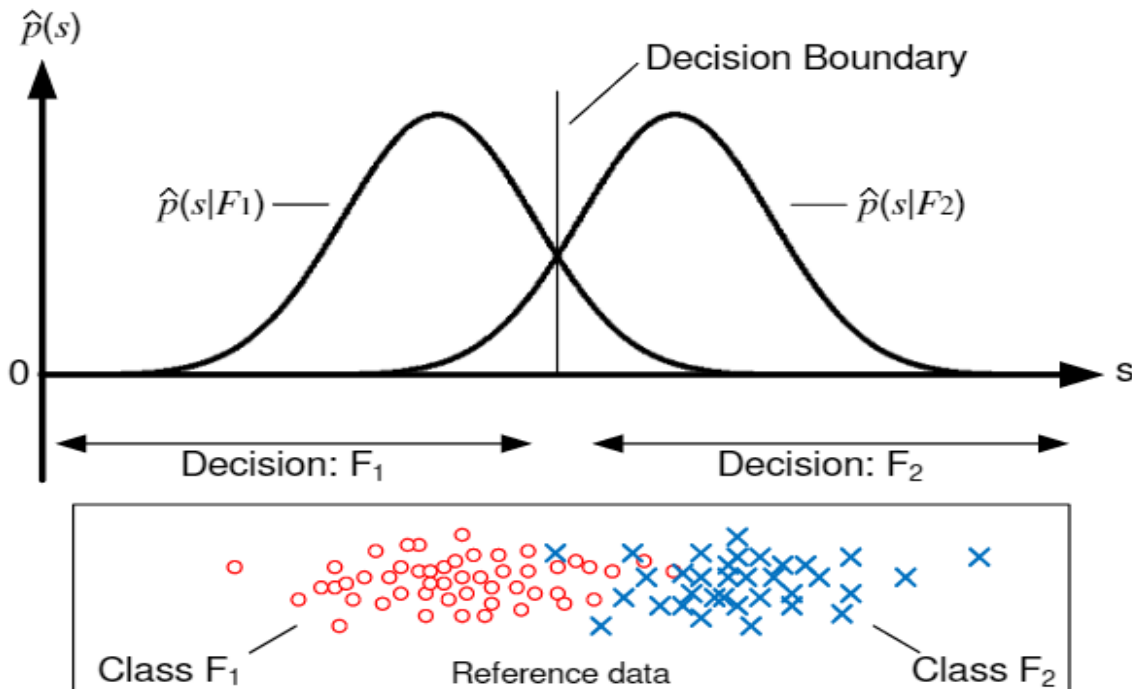


*Figure 15. Bayes Classifier [13]*

Assuming that prior probabilities $P(F_j)$ and class conditional density functions $p(\mathbf{s}|F_j)$ are given for all fault classes, then the joint probability density of identifying a fault $F_j$ that is associated with a set of symptoms **s** can be expressed with Bayes formula:

$$f_j = P(F_j|\mathbf{s}) = \frac{p(\mathbf{s}|F_j)P(F_j)}{p(\mathbf{s})}$$

The formula expresses that an observed set of symptom values updates value of prior probability *P(F_j)* thereby becoming A-posterior probability denoted as *P(F_j/s)* or in other words it states the probability that a fault class *j* will occur with regards to a set of symptoms that has been detected.

Main prerequisite to use Bayesian classifier is that the statistical properties of symptoms and faults must be known. Even though there are multiple ways of estimating these statistics from available data, this prerequisite put limit onto methods applicability. [13]

### 2.4.1.2. Geometric classifier – k-Nearest Neighbor Approach

This type of classification algorithms is simple yet quite rewarding. Principle of this method is that fault measure is determined as geometric distance between actual symptom vector **s** and a set of $n_r$ reference vectors $\mathbf{s}_{ref,l}$, $l \in \{1,\ldots,n_r\}$ for which the underlying fault $F_j$ is known.

The nearest neighbor algorithm is the most well-known approach within this classification method. The aim is to calculate the Euclidean distance $d_l$ between the actual vector **s** and the reference vectors. Fault class of the reference vector which is closest to the actual one is then believed to be the underlying fault (figure 9).[13]
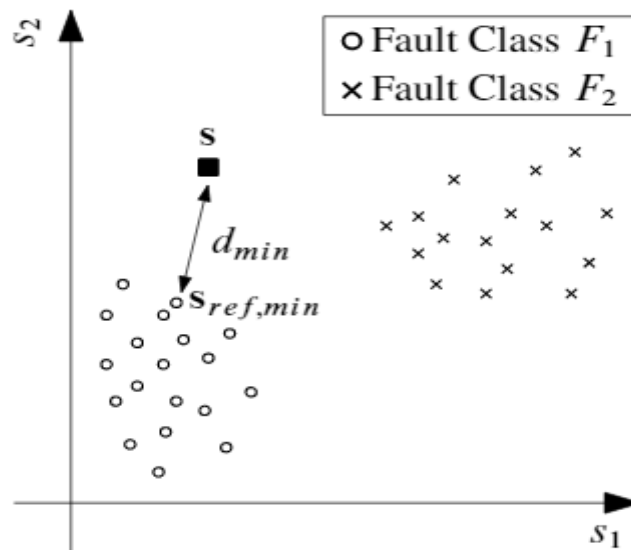


*Figure 16. Nearest Neighbor Approach [13]*

The nearest neighbor fault measures are calculated via following equation:

$$min(d_l) = min \sqrt{||\mathbf{s} - \mathbf{s}_{\mathbf{ref,l}}||^2}, l \in (1,\ldots,n_r)$$

### *2.4.1.3. Polynomial classifier*

In this approach it is assumed that the decision rule for determining faults is well enough approximated by polynomials in form of:

$$\mathbf{f}_j = a_{j,0} + a_{j,1}s_1 + a_{j,2}s_2 + \ldots + a_{j,n+1}s_1 s_2 + \ldots \quad . \quad (1)$$

Polynomial function is defined by coefficients:

$$\mathbf{a}_j = [a_{j,0} a_{j,1} \ldots a_{j,n_p}]$$

with $f_j$ denoting the fault measures for each individual fault class and $j$ being the target class with $n$ number of coefficients. If the polynomial order is 0 then the polynomial becomes identical to the linear classifier. In both cases functions presented in symptom-fault coordinate system form a hyper-plane that is used as basis for deciding if a given set of symptom values **s** belongs to fault $F_j$.

Vector $\mathbf{m}(s)$ represents individual multiplications of the symptoms $s_i$ of the input vector **s** meaning that all polynomial basis terms are included and represented as:

$$\mathbf{m}(\mathbf{s}) = [m_1, m_2, m_3, \ldots m_{n_{p,max}}]^{\mathbf{T}} = [1, s_1, s_2, \ldots, s_1^2, s_2^2, \ldots]^{\mathbf{T}}$$

On the figure 18 (following page) schematic structure of polynomial classifier is presented. Another term for structure of that type is *Π/Σ – Network*. All the elements of vector $\mathbf{m}(s)$ are first multiplied (symbol Π) with the coefficients $a_{j,i}$. Afterwards these expressions are weighted by means of loss function and summed (symbol Σ). Parameters $\mathbf{a}_j$ are determined using a least squares approach[4] thereby training the network to determine faults.

Once the parameter matrix **A** is determined polynomial classifier is applied in the following manner:

1. Evaluate all polynomials $f_1, \ldots, f_{nf}$ for a given set of symptoms **s**
2. Calculate the maximum value of all computed $f_j$ and determine its class label $j$
3. The set of symptoms **s** is associated with fault class $F_j$

When presented $n_s$-dimensional symptom space, each polynomial $f_j$ spans a hyper-plane. During classifier training process, each hyperplane attains such form that it minimises the loss function.

---

[4] This method is regularly used in regression analysis for approximating solutions of equation systems where there are more equations than unknown variables (overdetermined systems).

Hyperplane is formed only if order of polynomial is 3 or higher. From experience it is known that the $3^{rd}$ order polynomial is suitable enough for most applications. On the following figure two $2^{nd}$ order polynomial planes are presented in two-dimensional symptom space. If dealing with a two-class problem, there will be two (hyper) planes. The decision line between two faults is given by an intersection i.e. the location of line is where two polynomials have equal values, namely $f_1$ and $f_2$. [13]
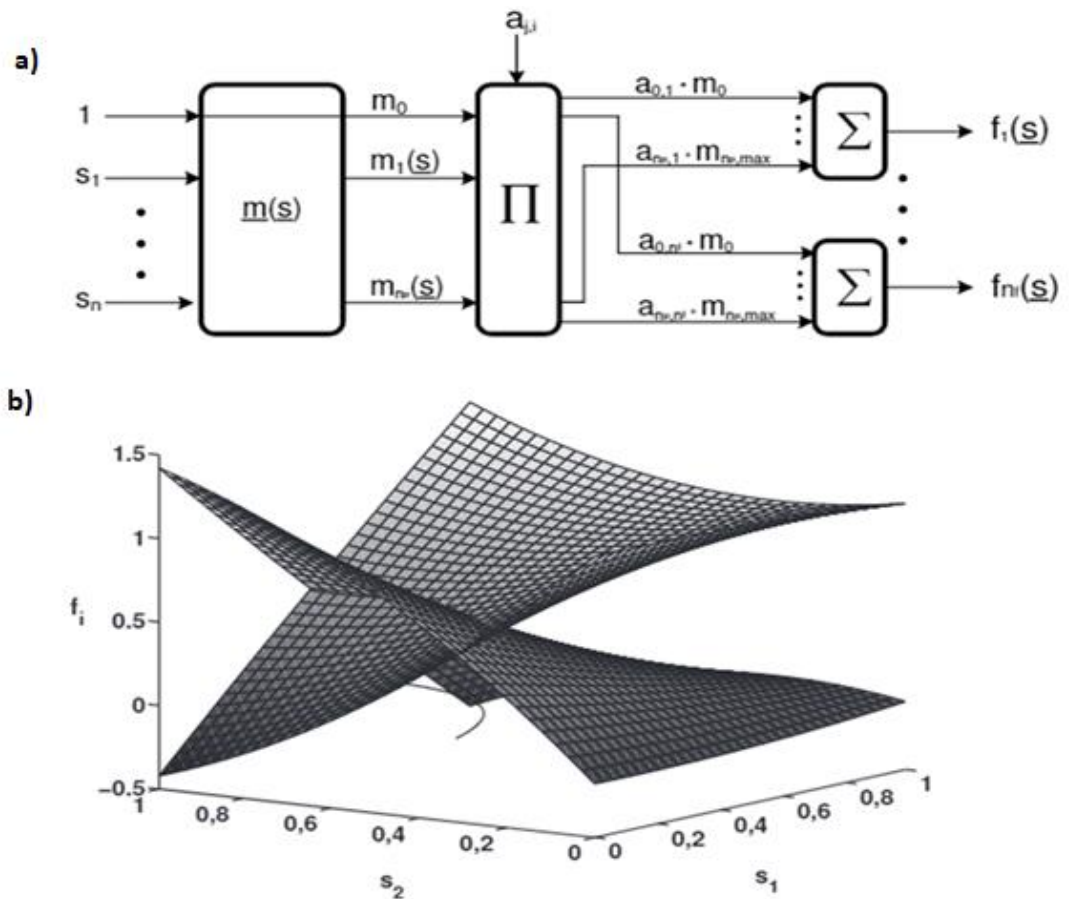


*Figure 17. Structure of polynomial classifier (a), intersection of polynomial planes (b) [13]*

### 2.4.2. Inference methods

In contrast to classification methods, inference can be used when basic relationships between faults and symptoms is at least partially known. Based on this theoretical knowledge, causal networks can be formed which follow this line of reasoning, namely:

fault →events →symptoms
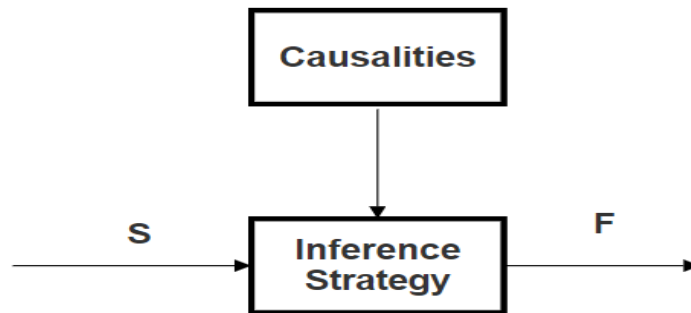


*Figure 18. Principle of fault diagnosis using inference methods [11]*

Relationships between the faults, events and symptoms are formulated in a verbal manner by means of logical operation IF<condition>THEN<conclusion>, which is yet another major difference between classification and inference methods. The premise (condition part) is input with facts in the form of symptoms S and the conclusion part is output that includes faults F as a logical cause of the facts. [11],[14]

#### 2.4.2.1. Fault tree (Event tree)

This method used in fault diagnosis provides good graphical and intuitive display of binary relations between symptoms, events and faults which are laid out in hierarchical way. Depending on its utility and situation in general, causalities can start from symptoms, branching to events[5] and finally arriving to the fault in question. This approach is called *forward chaining reasoning*[6]. If direction of deduction process is reversed so that procedure starts with a known fault with a goal of finding symptoms that have caused it, then it is called *backward chaining reasoning*[7].

The interactive relation of symptoms and events that can lead to the resulting fault is inferred by Boolean logic. If more than one symptom points to an event or fault, the facts are then related by AND and OR connection, leading to the rules in following form:

IF $\{S_1$ and $S_2\}$ THEN $\{E_1\}$, IF $\{E_1$ OR $E_2\}$ THEN $\{F_1\}$

---

[5] Besides literal meaning "events" can also be understood as internal logical variables.

[6] This term also refers to event tree analysis (ETA)

[7] This term also refers to fault tree analysis (FTA)

Once the fault tree is constructed, probability theory is applied in order to make quantitative analysis. In this way analytical treatment of events and symptoms is provided, given that data about failure probabilities is known.

Fault trees are usefully applied during the early system design phase to identify critical parts (subsystems) that are most likely to fail. However major disadvantage of this approach lies in binary logical decisions made by Boolean operators because it fails to capture the continuous nature of many diagnostic problems.[3],[11],[14]
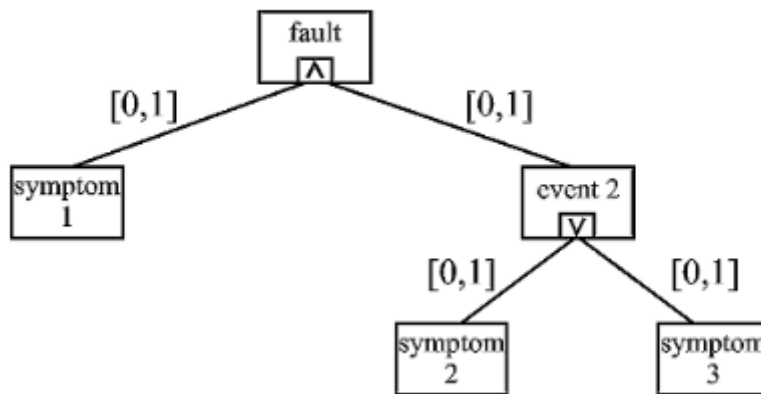


*Figure 19. Fault tree [14]*

### 2.4.2.1 Fuzzy logic

Shortcomings of binary evaluation of symptoms are mitigated by applying concept of fuzzy logic that was put forward in 1973. by Lofti A. Zadeh. It is a multivalued logic, that allows intermediate values to be defined between conventional (binary) evaluations like true or false, yes or no, high or low etc.

Fault diagnosis using fuzzy logic is achieved by means of inference engine (Fig.20) and requires several steps. First one is classification of symptoms (features) according to the degree by which their values match the membership functions. This type of functions is used to represent the degree of truth in fuzzy logic. In other words, symptoms are represented as fuzzy sets with linguistic meaning such as „small", „medium" or „large". Since their shape is trapezoidal, it accommodates values from lowest to highest possible and in between. Functions that lie close to one another overlap in non-horizontal area which expresses gradual nature of particular symptom.

After fuzzy sets are created, they are evaluated according to the IF-THEN rules previously set by experts of the field where inference engine is applied. Most commonly multiple rules will be applied to different membership functions. Outcomes of this step are combined (accumulated) using fuzzy-logic AND and OR operators.

Before such outputs can be used for determination of underlying fault, they first need to be defuzzied so the crisp values can be obtained, which are indispensable because processor calculations are in binary and not fuzzy form. Fuzzy outputs are mapped to the diagnosed fault when the maximum fault possibility is determined among all fault possibilities.[11],[14],[15],[16]



Rule Base: IF <Symptom $s_1$> = <normal> AND <Symptom $s_2$>=<increased> THEN <Fault $f_1$>
IF <Symptom $s_1$> = <reduced> AND <Symptom $s_3$>=<reduced> THEN <Fault $f_3$>

*Figure 20. Fuzzy logic inference engine [13]*

# 3. PRINCIPLES OF SEPARATION

## 3.1. INTRODUCTION

Heavy fuel oil (HFO) is used on marine vessels because it is economically very viable. Comparing to other types of fuels it has the lowest price for unit of volume. [17]. The reason lies in its quality as it besides hydrocarbons contains water, metal particles, vanadium, ash and carbon residues.[18],[19]. Two stroke and four stroke diesel engines, as well as oil fired boiler burners and incinerator tolerate such fuel composition. With appropriate operation and regular maintenance of those parts which are exposed to oil ignition and burning (injection valves, burner heads etc.) ship can operate using HFO far until ship is decommissioned.
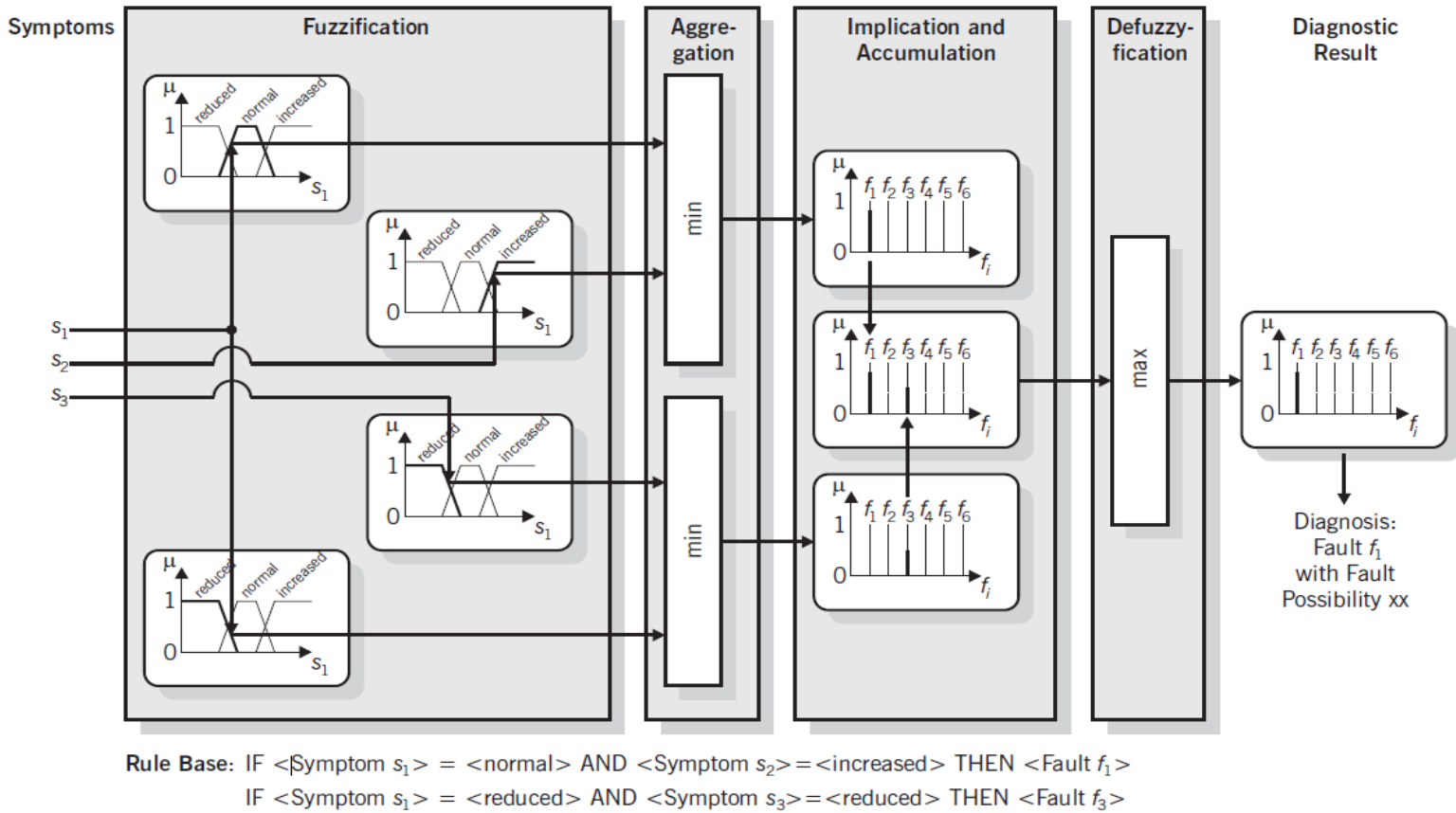
Physical process which is essential for achieving better fuel oil quality is the fuel oil separation. Units for fuel oil separation are installed on board ship and are, due to their function, crucial part of the engine-room fuel system. This chapter is focused on the separation process itself from physics perspective. Two types of separation processes will be discussed as well as all the factors which influence quality of separation.

## 3.2. GRAVITY SEPARATION – SEDIMENTATION

Most simple and oldest technique for separation is gravity sedimentation (settling). It takes place under influence of gravitational force in the fuel oil settling tanks. This is the first step in the process of fuel oil separation. Targets which are aimed to be separated are water and heavier solid particles found in fuel.

The process itself is only possible if there are differences in densities between multiple phases mixed together, for example fuel and water. According to [22] HFO RMA fuel has density of 920 kg/m$^3$ at 15°C while density of the water at the same temperature is approximately 1000 kg/m$^3$, so the conditions for separation are fulfilled and in given amount of time[8], water and heavier particles will settle at the bottom of the tank and will be drained by engine room crew member into sludge tank. On the other side it is possible that the fuel density is larger comparing to water, for example HFO RMK has density of 1010 kg/m$^3$ at 15°C. Such fuels are only stored in settling tanks, with no effective gravitational separation.

Separation of such fuels in only possible in separation units such as ALCAP[9], which will be presented and explained in chapter 5.

---

[8] Common practise for engine room crew is to leave fuel settling for 24 hours.

[9] Alfa Laval Clarifier and Purifier. Note: even though fuel density declines with rise of temperature, the density of some fuels at separation temperature still remains above water density

In theory, time and speed at which separation of solid particles as well as water takes place is defined by Stokes Law. It was derived in 1851. by English physicist and mathematician Sir George Gabriel Stokes most famous for his contributing to fluid dynamics in form of Navier -Stokes Equations. He formulated equation which defines how viscous force (also known as Stokes drag) affect spherical objects in viscous fluid.[20]

$$F_d = 6 \, \pi \, \mu \, R \, v \qquad (1)$$

Where $\mu$ is dynamic viscosity measured in $Pa{\cdot}s$[kg·m$^{-1}$·s$^{-1}$], $R$ is radius of spherical object [m] and $v$ is the speed at which particle is settling [m·s$^{-1}$]. This force has upward direction which means that it is inversely proportional to settling speed or to put it in another way, the larger force intensity is, the slower is particle settling speed.

In its application, following assumption must be taken into account: solid particles are spherical, and if not, the right-hand side of equation is multiplied with form factor for different object geometries. Also, particles do not interact with one another and flow is laminar due to is flowing velocity. [21]

According to Archimedes law when an object is immersed into fluid, buoyance force is exerted in upward direction with intensity equal to the weight of the fluid which is displaced by the object. [22] If downward gravitational force is equal to the buoyance force, the object floats.

Buoyance force $F_b$ and Stoke's drag $F_d$ combined together form force which resists to the process of gravity separation. Gravitational force $F_g$ acting downward, depends on: gravitational acceleration $g$ whose value is approximately 9.81[m/s$^2$], differences between densities of fuel ($\rho_F$) and water ($\rho_W$), or fuel and solid particles ($\rho_P$) in [kg/m$^3$] and the volume of particle (spherical) in [m$^3$]. In other words, gravitational force value determined by size and density of a particle.

$$F_g = (\rho_P - \rho_F) \cdot g \cdot \frac{4}{3}\pi \cdot R^3 \qquad (2)$$

When those two forces which act upon particle become balanced, particle acceleration stops and reaches so called „terminal velocity "($v_s$). It is the velocity at which separation takes place and is derived from equations (1) and (2).

$$v_s = \frac{2(\rho_p - \rho_f)}{9\mu} \cdot g \cdot R^2 \qquad (3)$$
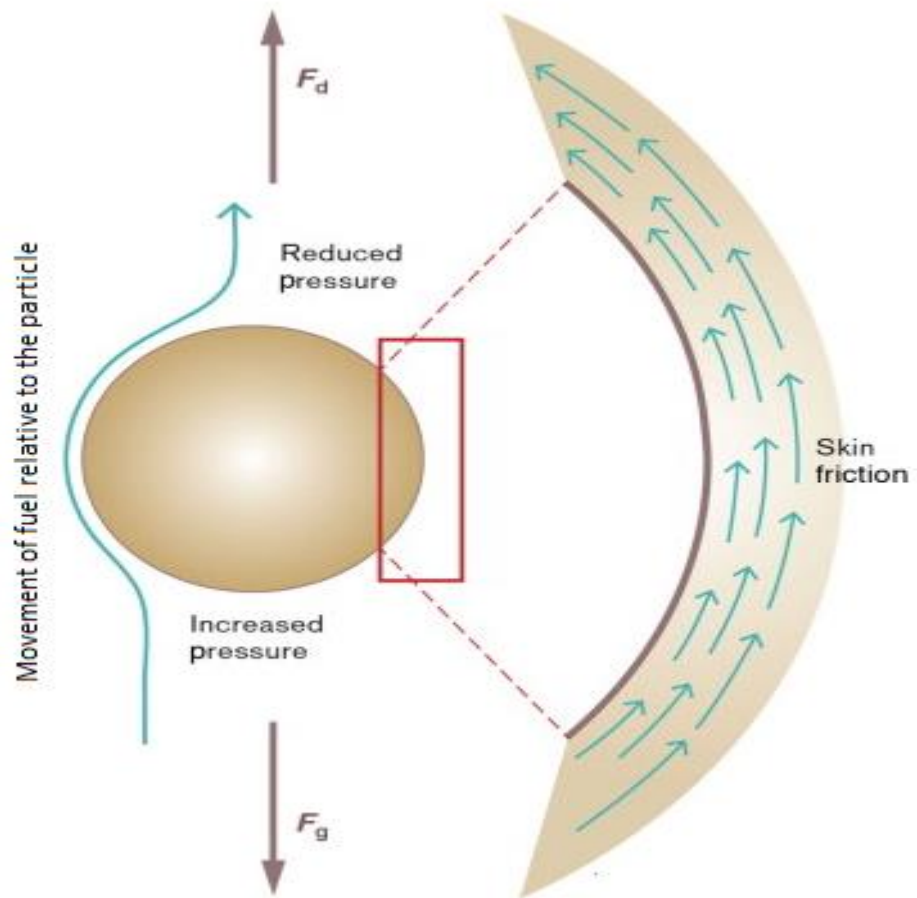
*Figure 21. Solid particle movement through the fuel oil [23]*

While particle is settling, drag force acts upon it. Its intensity is influenced by two factors. First being kinematics between the molecules of fuel which move relatively to the solid particle. Secondly, the drag results from the adhesion of fuel molecules to the solid particle namely, skin friction. Both types of friction are affected by fuel viscosity which dominates the drag on the solid particle. When the size of particle is small, flow of fuel around it is laminar. Such condition is referred to as Stoke's flow.[23]

Principles of Stoke's law are used when designing tanks in which fluids and particles settle. In the case of fuel oil, once the settling tank is filled via pump, no additional inflow takes place. That means that ideal case for such separation would be a shallow tank with large surface area because in such condition's separation would be faster and more efficient.

However this shape of settling tank would often prove useless on ships because heeling and pitching on sea waves would make efficient gravitational separation impossible. In order to mitigate such circumstances as much as possible, settling tanks are built tall and narrow. Such design also contributes to the more efficient way in which total ship's space is used for cargo space arrangement.
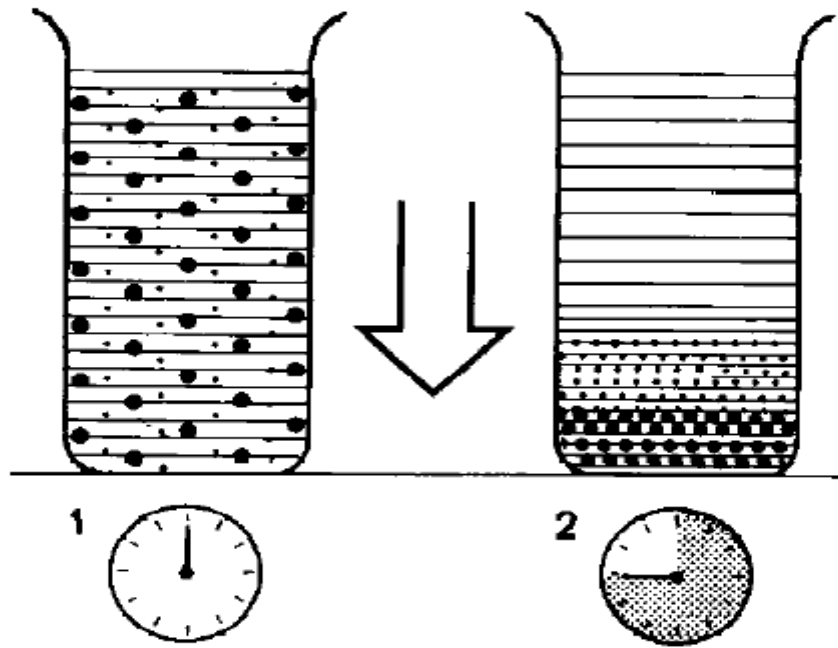


*Figure 22. Gravity separation – sedimentation [24]*

Even in perfect conditions, gravitational separation only partially removes water and solids from fuel. To achieve high quality separation, centrifugal force is used instead of gravitational, thus accelerating separation process and increasing its efficiency.

## 3.3. CENTRIFUGAL SEPARATION

Principle of centrifugal separation is presented on the following figure.
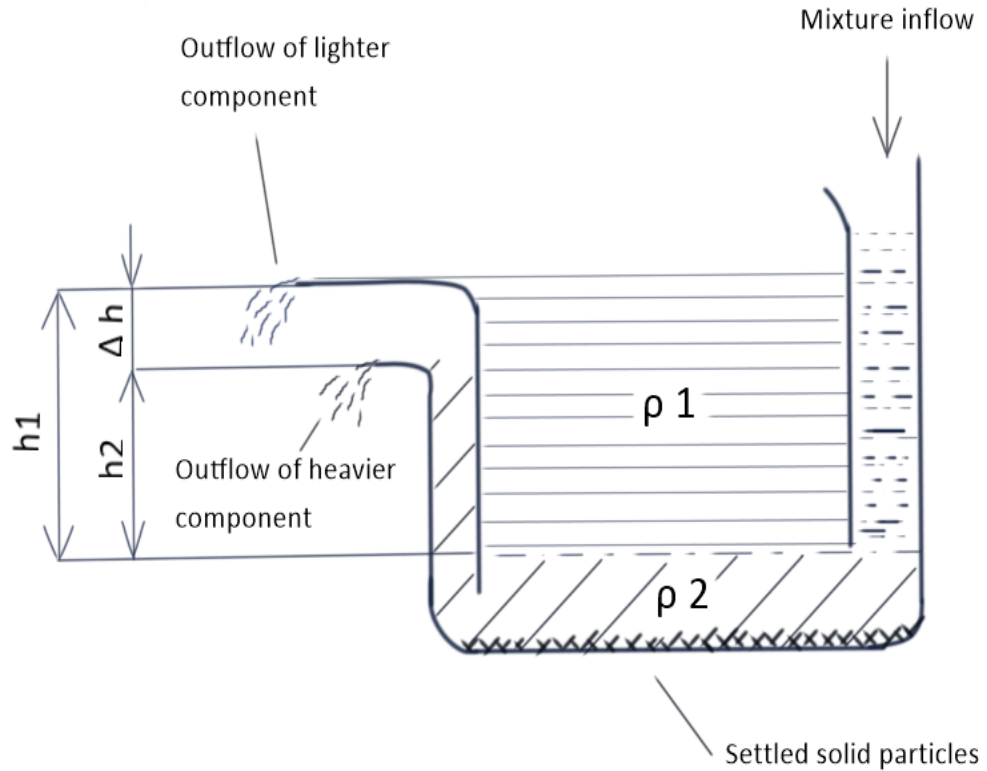


*Figure 23. Principle of centrifugal separation [18]*

In a specially designed bowl, a mixture of two phases[10] containing impurities is continuously fed though channel in the middle. Heavier phase ($\rho2$) is flowing at the bottom of the bowl while lighter phase rises above. On the other side of the bowl two phases are outflowing from edges whose height $h_1$ and $h_2$ are a function of density of the liquids. Solid particles are settling at the bottom of the bowl.

Difference in heights should be adjusted in a way that the hydrostatic pressure between two liquids is balanced, thus forming a line of separation. This is expressed as:

$$h_1 \cdot \rho_1 \cdot g = h_2 \cdot \rho_2 \cdot g \text{ from which follows that:}$$

$$\frac{\rho_1}{\rho_2} = \frac{h_2}{h_1}$$

---

[10] In the context of a centrifugal separator oil containing water and impurities (solid particles) are fed into the bowl, but this principle is applicable to any two fluids with different densities.

If the hight $h_1$ is too big, then hydrostatic pressure of lighter phase (oil) would displace heavier phase (water) thereby overflowing through the wrong edge. Similarly, if opposite situation takes place and height h1 is too low comparing to h2, water would contaminate pure oil outflow and separation would be futile. This principle is the basis of determining diameter of gravity ring, which will be described during this chapter.

So far only gravitational separation was discussed which takes place under influence of gravity field in which particles mass gains weight whose value is calculated when multiplied with gravitational constant (approximately 9.81 m/s$^2$).

If such bowl would be turned by 90° around its horizontal axis and mounted on a vertically set up shaft which rotates under certain angular velocity, basic centrifugal separator bowl would be created. Due to its rotation which can depending on design reach even 10 000 rpm, centrifugal field is created which seemingly[11] increases mass of a particles and thus increases speed and efficiency of the process of separation.
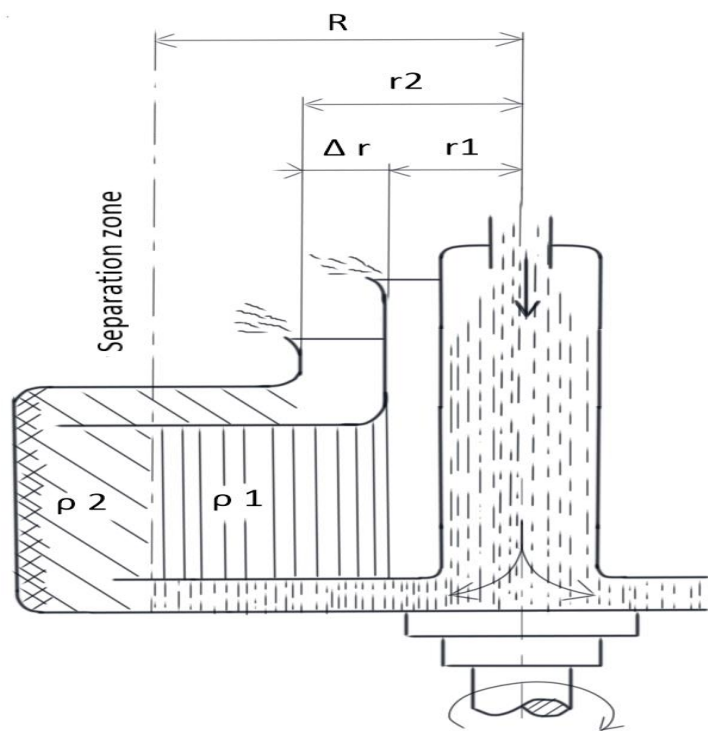


*Figure 24. Simple form of centrifugal separator [18]*

Molecular particles are now pushed against bowl walls with heavier ones being more distant from the centre of rotation. Height *h* is now replaced with radius *R², r²* since pressure rises with squared distance from rotation axis.

---

[11] One should be careful when describing properties of particles being in various force fields such as centrifugal. Mass of a particle remains constant, but the consequence of the particle being in such force field is as if the particles mass increased.

$$\rho_1 \cdot g \cdot (R^2 - r_1^2) = \rho_2 \cdot g \cdot (R^2 - r_2^2)$$

When solid particles with mass G are found in centrifugal field, they seemingly gain mass C which is determined with expression:

$$C = \frac{G}{g} \cdot r \cdot \omega^2 = \frac{G}{g} \cdot r \cdot (\frac{\pi \cdot n}{30})^2 = G \cdot r \cdot \frac{9{,}85}{9{,}81} \cdot \frac{n^2}{900} \approx \frac{G \cdot r}{900} \cdot n^2$$

From that it follows that the weight in centrifugal field is increased according to expression:

$$\frac{G \cdot r}{900} \cdot n^2$$

If $r$ is taken to be 0.1 m and n = 10 000 rpm it follows:

$$C = \frac{G}{g} = \frac{0{,}1 \cdot 10\,000^2}{900} = 11\,100$$

This result means that the apparent weight of a particle in such centrifugal field will be 11 100 times bigger, then it would be under influence of gravitational field. In such conditions, mutually mixed fluids which are continuously fed into the bowl are easily and efficiently separated. This is the main reason why centrifugal separators are used for both mineral and fuel oils.

Centrifugal settling velocity is calculated by solving Stoke's Law equation [72]:

$$V_c = \frac{d^2(\rho_w - \rho_0)}{18_\mu} r\omega^2$$

where $V_c$ is centrifugal settling velocity [m/s], $d^2$ is a droplet diameter [mm], $\rho_w$ is heavy and $\rho_0$ is light phase density in [kg/m³], $\mu$ is continuous phase viscosity [kg/ms] and $r\omega^2$ is centrifugal acceleration.

Prerequisite for successful separation is that components of the product: can be separated mechanically, have different densities, and do not emulsify.[18]

# 4. DISC STACK CENTRIFUGAL SEPARATOR

Today on-board marine vessels separation of fuel oils and mineral oils is indispensable process which is carried out by means of marine centrifugal separators.

In 1875. was the first time that the principles of centrifugal separation were embodied in a form of device. German professor in field of dairy farming - Alexander Prandtl, improved his brother's ideas of using centrifuge to separate cream from milk, thus creating butterfat extraction machine.

About the same time, in late 1870's Swedish engineer, inventor Gustaf de Laval who was founder of Alfa Laval Company, presented his first continuous centrifugal separator for cream thereby revolutionising diary industry as well as industry in general. These inventions paved the way for oil separation using disk stack technology which began in early 1900s.

In 1917. Alfa Laval delivers oil separators[12] which are installed by US Navy with purpose of breaking water emulsions in lube oil on vessels propelled by steam turbines. By 1930. Alfa Laval launches new series of improved separators which are specially developed for marine industry. Since then, separators have seen great technological improvement in terms of efficiency, materials, intervals for maintenance and level of automatization. Many manufactures such as Alfa Laval, Gea Westphalia, Mitsubishi and others have designed centrifuges which differ in greater or lesser detail. Nevertheless, every purification system is made of same subsystems, namely: feed system, bowl assembly, driving unit with frame, control plus monitoring system and hydraulic system for sludge discharge, all with its belonging elements.

All mentioned components besides complete feed and control system can be seen on following picture which shows modern centrifugal separator from Gea Westphalia manufacturer. It can work both as purifier and clarifier[13].[25]

---

[12] From this point onward, the term separator is referred to centrifugal disc stack separator for purifying fuel, mineral and synthetic oils.

[13] Difference between the two and the context of their application will be described in greater detail during chapter 4. If it is equipped with UNITROL system, then it works as clarifier and purifier at the same time. Principles of such system will be presented in chapter 5.
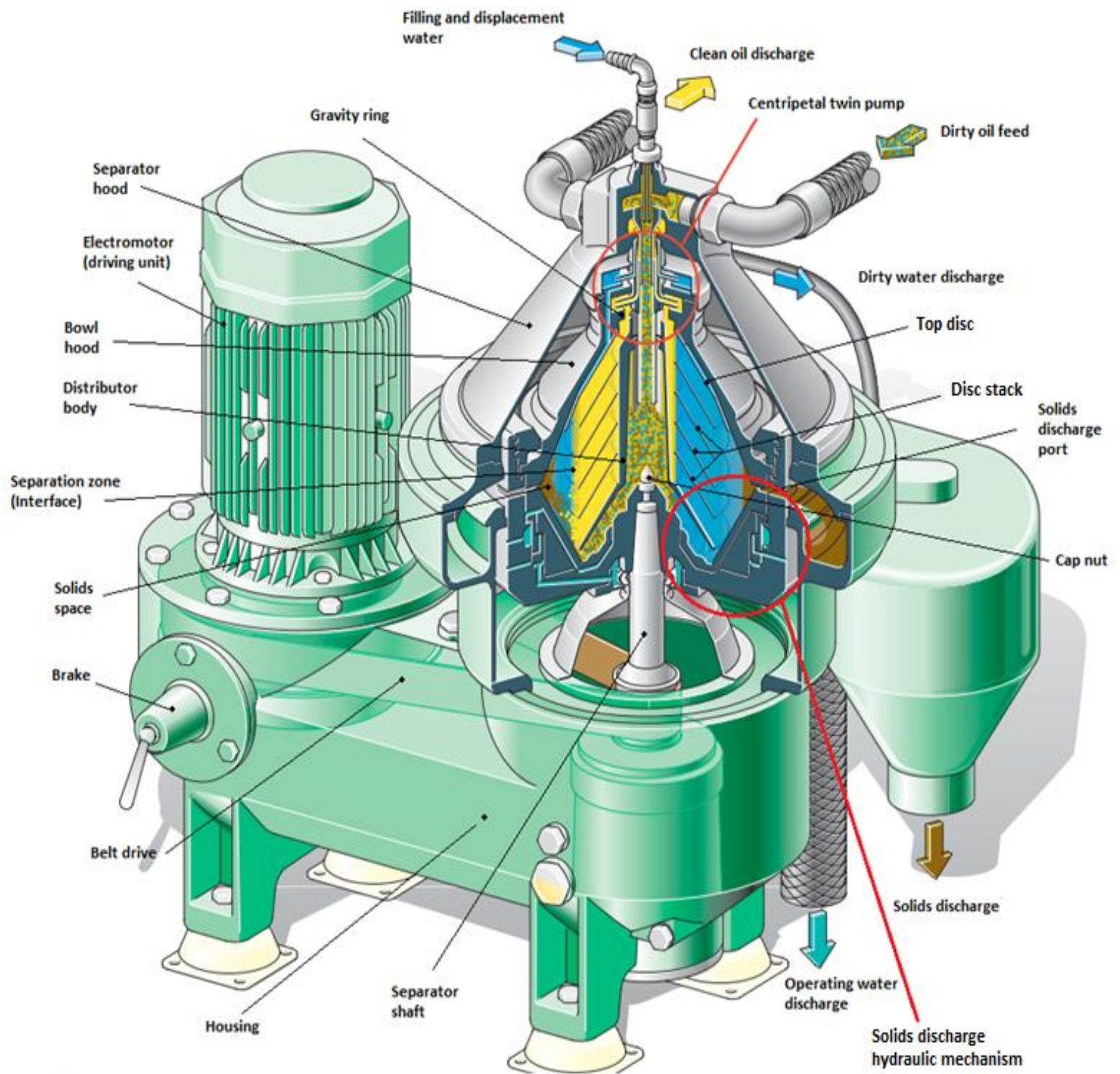
*Figure 25. Gea Westphalia Self-Cleaning separator* [26]

## 4.1. SUPPLY SYSTEM

Purpose of this system is to deliver and prepare oil in such manner that it is in optimum state for separation. Feed pump[14] draws oil from settling tank and delivers it under pressure through the heater to the separator inlet. Strainer is situated on the suction side of the pump which should be regularly inspected if the drop of pressure on suction side of the pump is noticed. Pump's pressure can be adjusted via tension or slack of non-return valve spring or by adjusting fuel regulating valve and should be kept on the level suggested by the manufacturer.
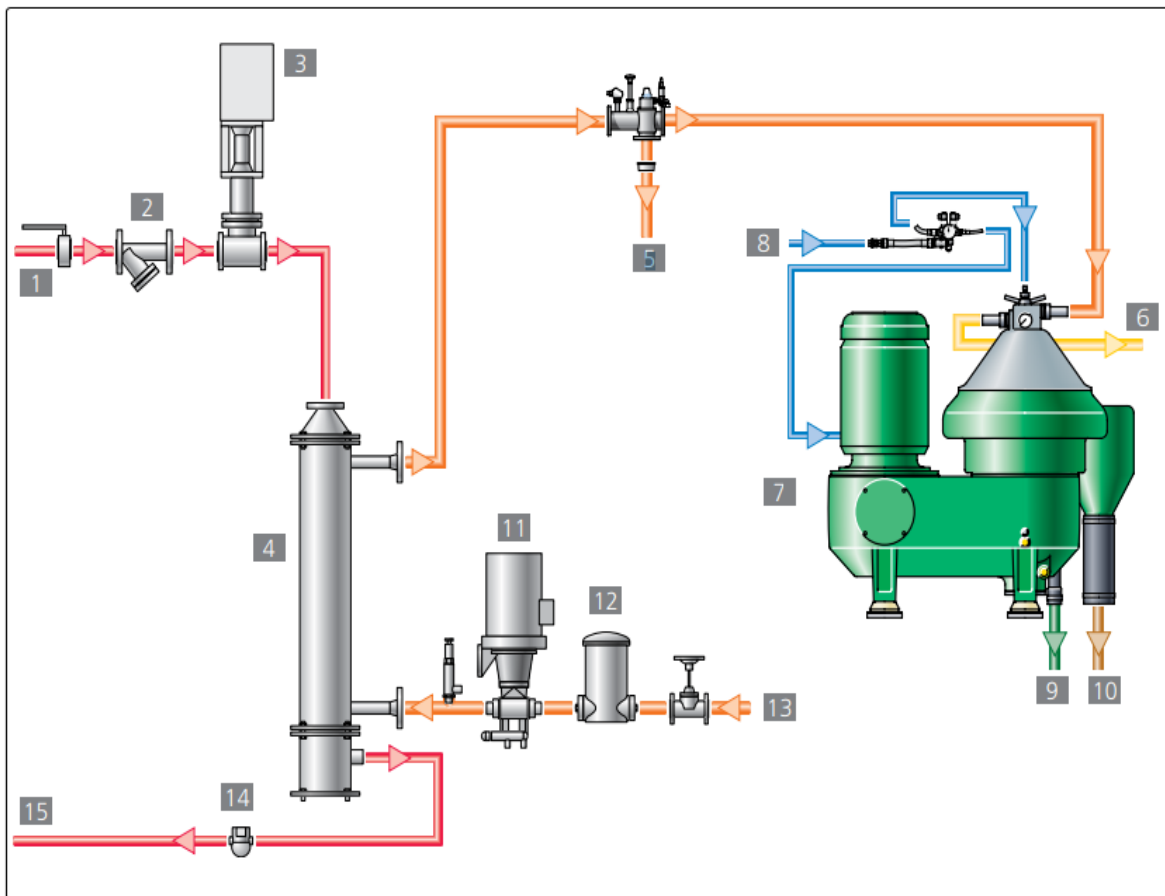


| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1 | Steam | 5 | Dirty oil return | 9 | Dirty water discharge | 13 | Dirty oil feed |
| 2 | Strainer | 6 | Clean oil discharge | 10 | Solids discharge | 14 | Steam trap |
| 3 | Regulating valve | 7 | Self-cleaning separator | 11 | Feed pump | 15 | Condensate |
| 4 | Preheater | 8 | Operating water | 12 | Filter | | |

*Figure 26. Separator supply system [26]*

---

[14] Depending on the design they can be gear or screw pumps. They are constructed to work well with viscous fluids like oils.

Before oil mixture is introduced into separator it passes through three-way dirty oil return valve also called recirculation valve. Whilst in first position dirty oil is fed to the separator. In case of automatic[15] sludge discharge or failure (for example loss of water seal), control unit changes position of valve so the oil is return to the settling tank (case HFO separator) or sump tank (case LO separator).

In this way, oil is prevented from draining into sludge tank. Flow measuring instrument is mounted on the separator feed pipe so engine crew member can check dirty oil flow value.

### 4.1.1. Oil heating

Depending on the purification system design, tube or plate steam-heater is installed so the oil temperature increases before entering the separator.[16] This process is necessary as by increasing the temperature, viscosity of oil drops. According to Stoke's Law, drag which is exerted upon the particle in viscous fluid is directly proportional to its viscosity, meaning higher temperature leads to lower viscosity thus easier separation process.

On the other side there is a limit to how high temperature can be. According to [28], lubricating oil is separated at temperature kept around 88-89°C while more viscous HFO around 98°C. Oil temperature should be kept below 90°C in order to avoid oil deterioration due to heating. At those temperatures water evaporation of mixture, as well as water seal[17] is still not possible[18], thus avoiding all potential difficulties arising from the presence of water vapour in the separation system.

Inflow of steam through oil pre-heater is regulated with heater control valve. Valve actuator receives signal from the controller and sets position of the valve according to the set temperature.

---

[15] Details regarding separator operation procedures and automatic control will be presented in chapter 5.

[16] Besides steam-heated oil heaters, additional auxiliary electric heater is often installed as an auxiliary device for oil heating in special situations. (e.g. vessel is in the dry dock and steam boiler is shut down, or steam-heater needs immediate repair)

[17] Before oil mixture is introduced into separator, bowl is filled with water. This water forms so called "water seal" which acts as a physical barrier with function to prevent clean oil outflow in water outlet. On the figure 25 it is labelled as $\rho_2$.

[18] At the atmospheric pressure water evaporates at 100 °C, but since in some purifying systems oil feed pumps pressure can range from 2.5 to 3 bar [30], the boiling point is extended even more. However, safety margin is considered and therefore applied.

Heated oil is then led through flow control valve thereby regulating oil pressure and flow to the purifier. Value of flow must meet demand of fuel oil consumption, but at the same time satisfy quality of purified oil.

### 4.1.2. Separation quality

Besides temperature adjustment there are several more factors which influence quality of separation. Simulations #1 and #2 are run so as to show relationship between throughput (settling time) and quality of separated oil. When LO (Lubricating oil) separator is running with 30 % of maximum gravity ring[19] diameter, the index of solid particles (dirt) in the clean oil outlet is 4.86 %.

When the feed pumps speed index[20] is decreased from 50 % to 30 % thereby reducing flow from 2000 kg/h to 1200 kg/h dirt index is lowered to 1.82%. One can conclude that these two variables are inversely proportional meaning that larger flow is achieved at expense of lower separation quality.

Another factor that determines separation quality is the shape and size of particle (figure 28). The round and smooth particle (A) is more easily separated out than the irregular one (B). Particles take final form after the process of fuel distillation and treatment in refinery is over, but they can be further reshaped during rough treatment for instance in pumps. Larger particles (1) are more easily separated than smaller ones (2) even if their density is equal.[27]

---

[19] Details, role, and effects of gravity ring diameter will be explained in the next section: 4.2. „Bowl assembly "

[20] In case of LO separator the flow is regulated via changes in the pump operating regime instead of flow control valve. Such designs are common.
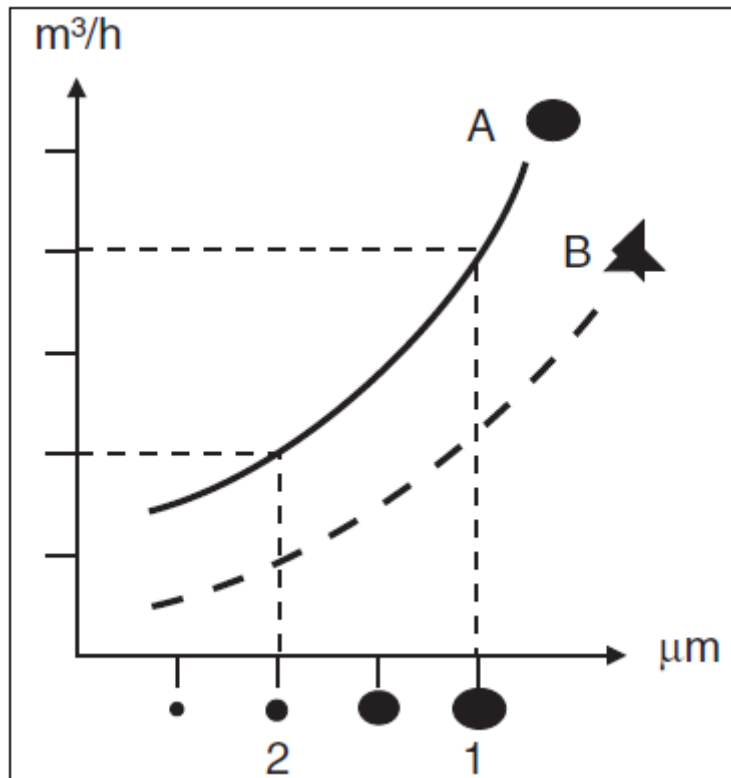
*Figure 27. Influence of size and shape on separation quality [27]*

### 4.1.2.1. Parallel and series operation

Classical way to influence quality of separation and total oil flow value is by putting another separator into operation. Because of redundancy requirements, fuel purifying system has always one or more additional (stand-by) separators. If they work in parallel regime the separation capacity is increased[21].

Contrary to parallel operation, two separators can be put into series operation. This is common practise when it is suspected that HFO has excessive sludge, water, or catalyst mixture[22]. Then the outlet of first separator becomes inlet to the second.

Under such conditions flow value remains constant with slight pressure drop that should be inspected by engine crew member. Feed pump and heater of second stage are out of operation since they are not necessary.

---

[21] When using Norcontrol Neptune MC90 simulator, when second HFO separator is put into operation, separation capacity is increased for 83 %, but the water content in outlet grows double fold.

[22] Parallel regime with decreased fuel pump flow index is sometimes recommended by separator manufactures when dealing with fuels that are dirtier then average, so choosing between series and parallel regime depends on the details of situation in question.

Today's purifying systems are equipped with monitor-control system. During the discharge phase oil feed to the first stage is stopped. Naturally, pressure drop will occur in the second stage. One of the common faults of purifying system are leakages whose best indicator is pressure drop. Monitoring system will detect such event and sound the alarm. This will be foreseen by the engine room officer who will activate control system interlock in order to prevent false leak monitor output signal.

Finally, some other modification on the second stage separator must be made so that remaining solid particles which are finer in size and shape can be separated thus achieving high quality separation. Separator operating in second stage is called clarifier, whilst the one in first stage is purifier.

### 4.1.2.3. Changing purifier to clarifier

Elements which differentiate first stage from second make up the constructional difference between purifier and clarifier. Since the water has already been separated by purifier, gravity ring is replaced by blind disc (also called „dam ring "). Clarification is a two-phase separation, with sealing water providing physical barrier, so that the lighter phase – oil does not exit through wrong outlet. Blind disc covers the second outlet, so the clarifier has only one outlet namely for clarified oil. Also piping for sealing water must be closed since it is not needed in second stage.

Finally, first disc at the bottom of the disc stack must be replaced with one that has no holes so that remaining solid particles are guaranteed to reach the furthermost periphery of the bowl[23] namely sludge space thus achieving maximum quality separation.

### 4.1.3. Catalytic filter

Last element to describe in this chapter is catalytic fines filter. Its relation to this topic is due to function and not location since its installation point is determined so to provide optimal effect in fuel circulation line.

Although separation process, especially if run in series, removes catalytic fines[24] from fuel, some of them can still be found in fuel injected in engine cylinders thereby causing damage to cylinder liners, piston rings and fuel pumps. Automatic 10-micron filter with backflush capability makes a good preventive solution for safer engine operation.

---

[23] More detailed description of the elements which make up the separator bowl, followed by illustrations can be find in next chapter (4.2) "Bowl assembly".

[24] Catalytic fines are very hard particles which are used as catalyst for refining extremely low sulphur fuels.
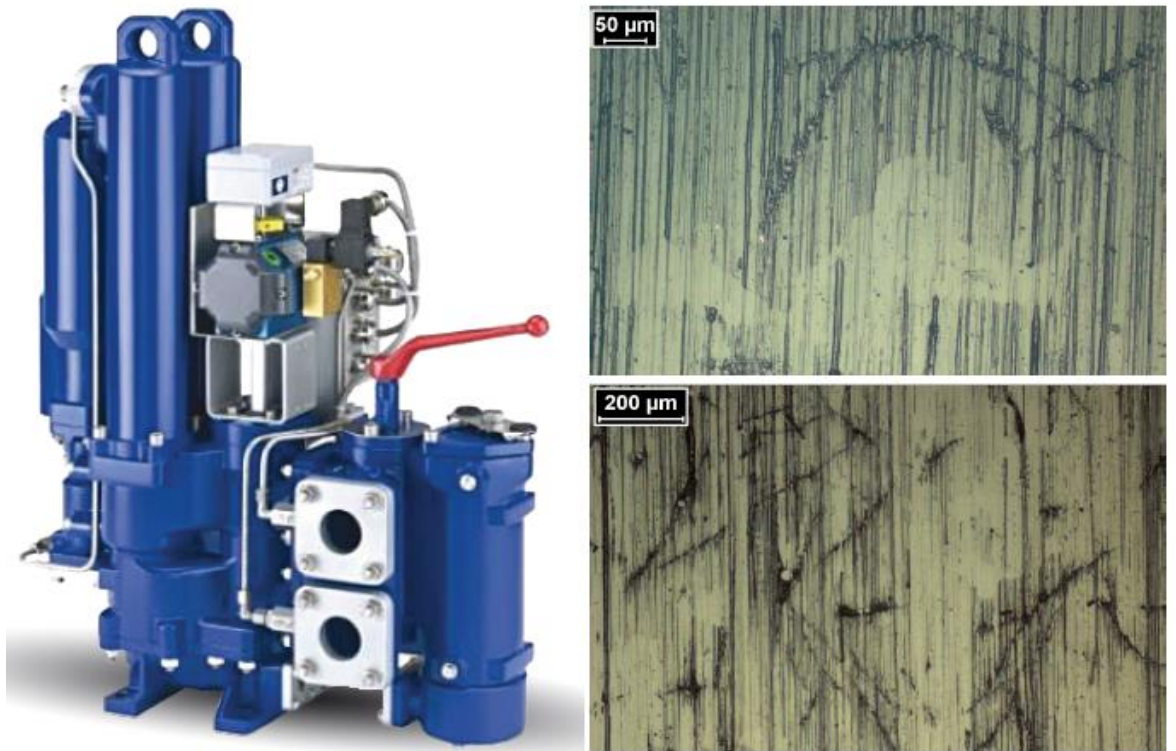
*Figure 28. Catalytic fines backflush auto-filter (left), damage caused by catalytic fines to cylinder liner (right) [29]*

## 4.2. BOWL ASSEMBLY

Construction of purifier bowl assembly is shown on the following figure:
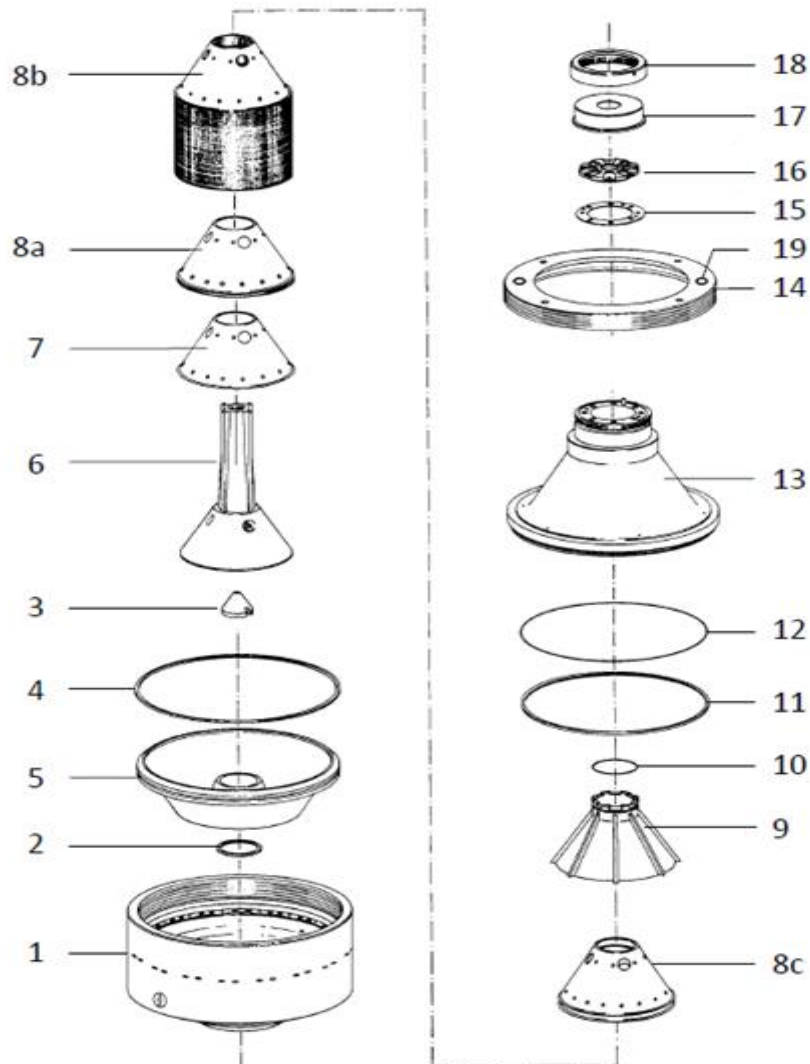


*Figure 29. Bowl assembly [30]*

Parts that are marked by numbers are as following: 1-Bowl body, 2- OR gasket – bowl body, 3- Bowl body nut, 4- Gasket, 5- Moving ram, 6-Distributor, 7-Bottom disc, 8abc – Intermediate disc, 9-Finned upper disk, 10- OR gasket, 11-Nylon gasket – bowl hood, 12- OR gasket – bowl hood, 13- Bowl hood, 14 – Big lock ring, 15- Drilled gasket – dividing disc, 16 – Dividing disc, 17 – Finned cover, 18 – Small lock ring, 19- Screw

Before the process of separation begins, separator bowl is filled with hot water which forms *water seal*. Through the same axial tube called *distributor* located in the middle of separator, dirty oil is supplied downward to the bottom of the bowl where it gets evenly distributed via guided fins across the bowl and accelerated to the rotational velocity of the bowl.

### 4.2.1. Disc stack

It is comprised of many conical discs which are fitted with spacers that hold them about 0.3-0.5 mm apart thereby creating precise interface between individual discs. Discs are pressed together by means of bowl hood. While separator maintenance is carried out, force which clamps discs in place must be set correctly, otherwise bowl balance is affected which leads to vibrations and shorter life of ball bearings.

Along its radius they have one or two series of bores radially distributed so the fluid can move upwards with less resistance. The surface is smooth, so it facilitates sliding of the solids and hence self-cleaning of the discs. Due to its specific gravity oil flows closer to the centre of the bowl in contrast to water and solid particles which are pushed to the periphery under influence of centrifugal force.

According to figure 25. separation process could be achieved without disc stacks, but such separation would be highly inefficient comparing to the separation with disc stacks.

Purpose for implementing disc stacks is on one hand related to the shape of the bowl. In the past tubular bowl shapes with large height to radius ratio were used. Such could withstand much higher angular velocities, resulting in higher centrifugal (separation) effect. Furthermore, heavier phase (water) and solid particles had to travel shorter distance before reaching bowl wall. Water was guided to the water discharge while solid particles deposit on the wall. Effect was faster separation process.

Disadvantage however lied in the smaller sludge retention volume thus more frequent manual or automatic sludge discharge[25] was required. Bowl height could be increased only to a certain limit to avoid balancing and handling problems, thus constraining such bowl design.

Today different bowl design, with smaller length to radius ratio i.e., wide bowl shapes are used. Their advantage is retention of more sludge (solid deposits) before its performance is impaired thus less frequent manual or automatic sludge discharge is required. Furthermore, it is easier to maintain them since they are easier to clean. Their disadvantage lies in worse settling characteristics towards the bowl centre since water and impurities must travel bigger distance to reach bowl wall. Solving disadvantages related to wide bowl is accomplished by means of disc stack which act as extended settling surfaces.

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[25] Further analysis will be presented in following chapter 4.3. Sludge discharge system

On the other hand, fitting disc stack enlarges the settling surface by great amount therefore increasing separator capacity. Solid particles collide with underside of discs and accumulate. Because centrifugal force overcomes force resulting from upward movement of the fluid, solid particles eventually slide along the discs towards periphery. They eventually reach and settle at bowl wall (sludge space) while water globules rise and leave the separator through dirty water discharge outlet.

Bowl is fitted with numerous holes radially displaced along its periphery. They are means by which accumulated solid particles leave the sludge space once its volume has reached maximal capacity. Outlets for dirty water and clean oil are situated in upper part of bowl assembly. [31],[32]
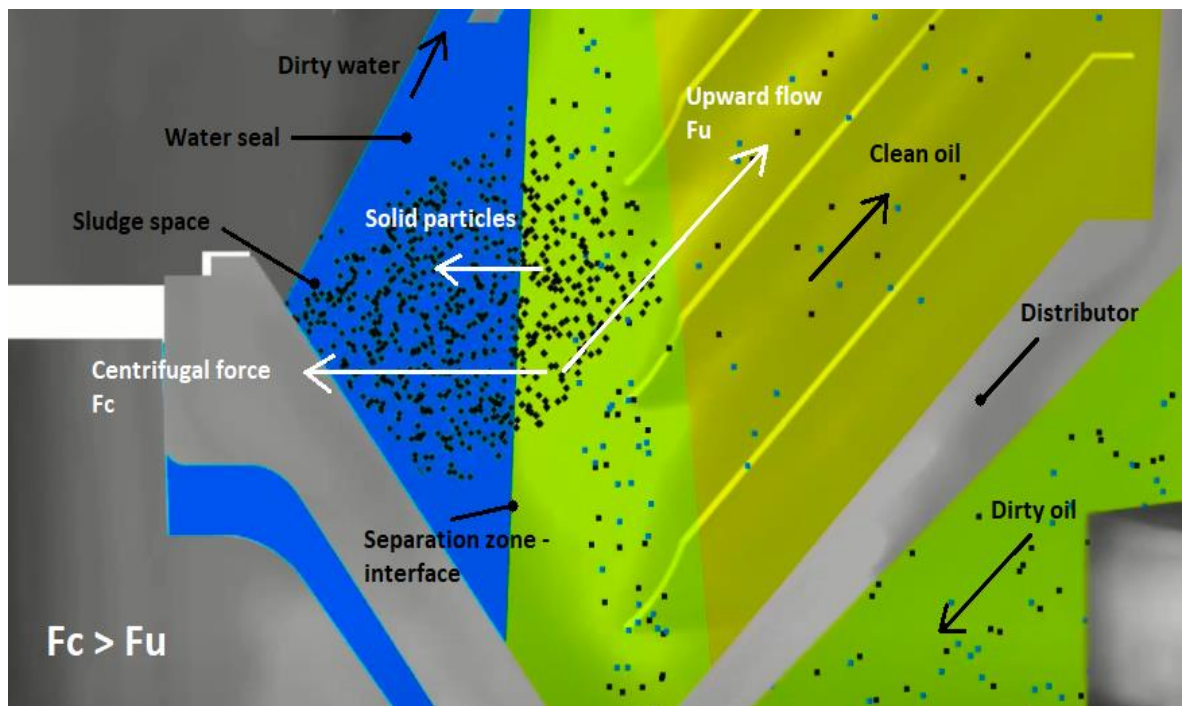


*Figure 30. Disc stack separation [32]*

### 4.2.2. Gravity ring

Gravity ring is mounted on the dirty water outlet. Hydrostatic pressure which water exerts on lighter phase (clean oil) is a function of gravity ring diameter and once pressures are balanced, interface also known as *e-line* is formed.

Its position is crucial for overall separation result. From theoretical calculations which were verified by empirical results, fullest utility which disc stack can provide is gained if separation zone is located outside of it, but still inside diameter of top disc. Top disc is larger comparing discs fitted in stack and acts as water outlet baffle.

*Figure 31. Detail of top of the classical purifier [33]*

By using Neptune Norcontrol MC90 Simulator, separator operation with different size of gravity ring is simulated.



*Figure 32.  Simulation of LO separator with table parameters [27]*

Results are shown on following table:

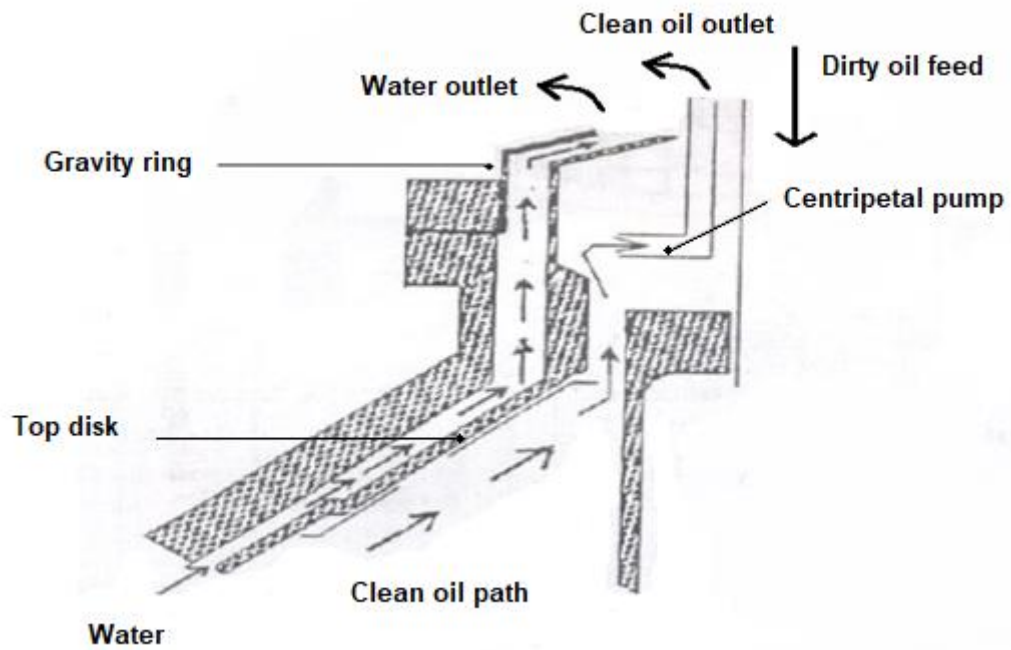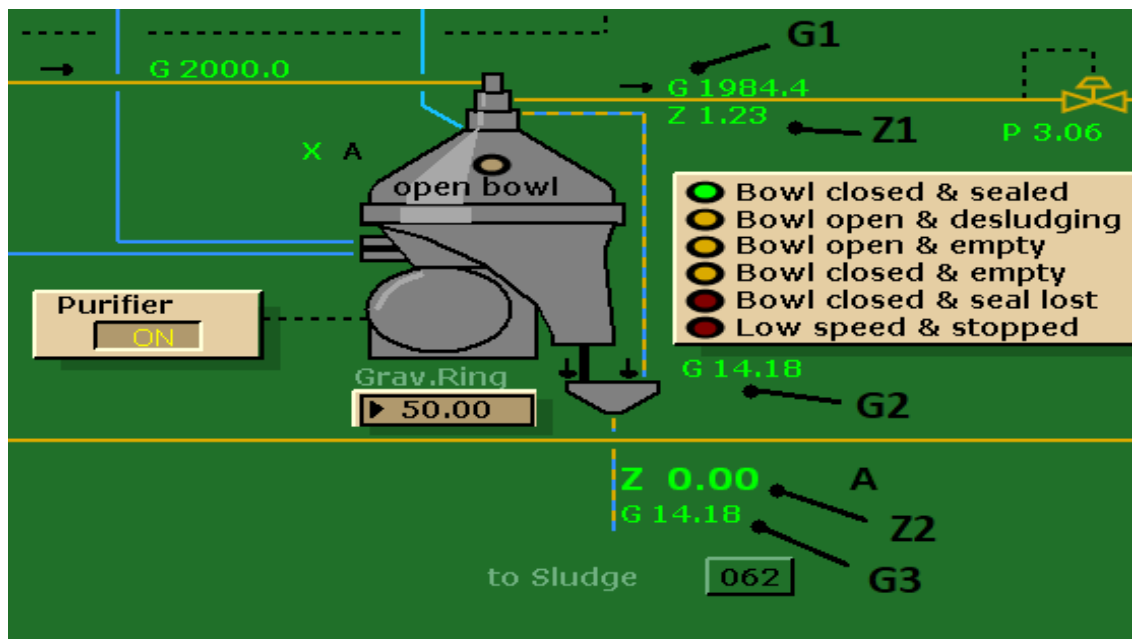| Gravity ring diameter [%], 100 = max ring diameter | G1 – purifier clean oil outlet [kg/h] | G2 – purifier sludge flow [kg/h] | Z1-purifier outlet dirt index flow [%] | Z2-purifier sludge oil index flow [%] | G3 – purifier total waste flow [kg/h] |
|---|---|---|---|---|---|
| 0 | 1984.4 | 12.86 | 12.26 | 0 | G2=G3 |
| 10 | 1984.4 | 13.13 | 9.69 | 0 | G2=G3 |
| 20 | 1984.4 | 13.39 | 7.19 | 0 | G2=G3 |
| 30 | 1984.4 | 13.65 | 4.86 | 0 | G2=G3 |
| 40 | 1984.4 | 13.91 | 2.81 | 0 | G2=G3 |
| 50 | 1984.4 | 14.18 | 1.22 | 0 | G2=G3 |
| 55 | 1984.4 | 14.31 | 0.66 | 0 | G2=G3 |
| 56 | 1984.4 | 14.33 | 0.57 | 0.02 | G2=G3 |
| 60 | 1972.7 | 25.56 | 0.27 | 16.48 | G2=G3 |
| 61 | 1960.9 | 36.16 | 0.22 | 30.71 | G2=G3 |
| 62 | 0 | 36.16 →6486 →0 | 0 | 0 | G2=G3 |

*Table 1. Simulation parameters as a function of gravity disc diameter*

*[source: author]*

This simulation shows necessity of choosing correct size of gravity disc diameter. As the diameter increases from the minimal possible, one can notice increase in sludge flow *G2* and decrease in dirt *Z1* contained in clean oil outlet. Generally, when the gravity ring is too small, separation line will be too close to the centre of rotation. This will result in water contaminating clean oil outlet.

At 55% of maximal gravity ring diameter, the amount of sludge flow *G2* is the greatest with low dirt index *Z1* in the clean oil outlet (just 0.66%) with no oil in water outlet discharge[26]. That means that separation line i.e., interface is not too distant from centre so that clean oil gets lost in water discharge outlet. Simulation shows that 55% is optimal gravity ring diameter size for this separator and type of oil separated because at 56% one notices that sensor in sludge discharge line now registers 0.02 % of clean oil. That means that some amount of oil is lost though water outlet during separation process which of course is not proper way to operate oil separation system.

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[26] Water contained in oil and sludge are discharged in the same tank usually located beneath separator called separator sludge tank.

If gravity ring diameter is further increased, purifier clean oil outlet *G1* flow starts to decrease. More and more oil is getting lost through water outlet leading into sludge tank. Finally, at 62 % separation line has passed the outer edge of top disc and water seal breaks. In such cases oil fed into the separator leaves separator bowl through wrong outlet. Control unit registers such event and opens recirculation line preventing oil loss into separator sludge tank. Separator is stopped and requires inspection before being put into operation again.

Correct size of gravity ring can be determined experimentally or calculated using diagram and relevant data. Experimental approach is based on trial and error. First one starts with large diameter ring. If the clean oil is found in the water outlet, then next smallest one is chosen and tested. On the other hand, when too small ring is inserted then the emulsification of clean oil is expected. When enough iterations of experiment are done, one arrives at correct size and observes that the process of separation is taking place in proper way. Besides using water and oil sensors, alternative way to check if the proper size of gravity ring is correctly chosen is by inspecting underside of bowl disc.
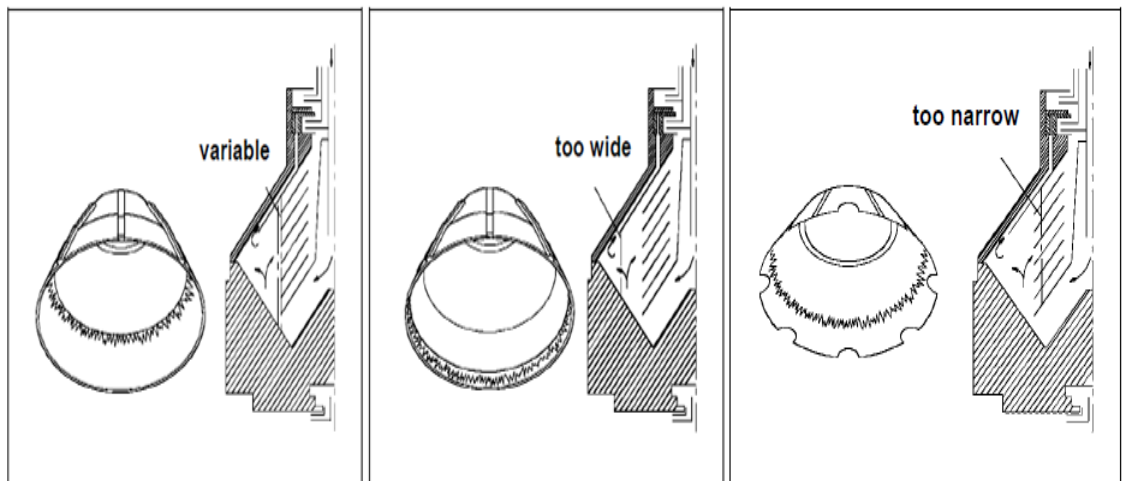


*Figure 33. Relationship between gravity ring diameters and position of separation line [34]*

Easier and less time-consuming approach to determine the correct gravity ring diameter is by aid of graph. Additionally, oil density at separation temperature can be determined. Given data are density of oil at 20 °C - 0.89 kg/dm$^3$ and separating temperature $t = 70$°C. The diagram on the next page is shown as an example of how required gravity ring diameter is found as a function of separating temperature and the oil density.
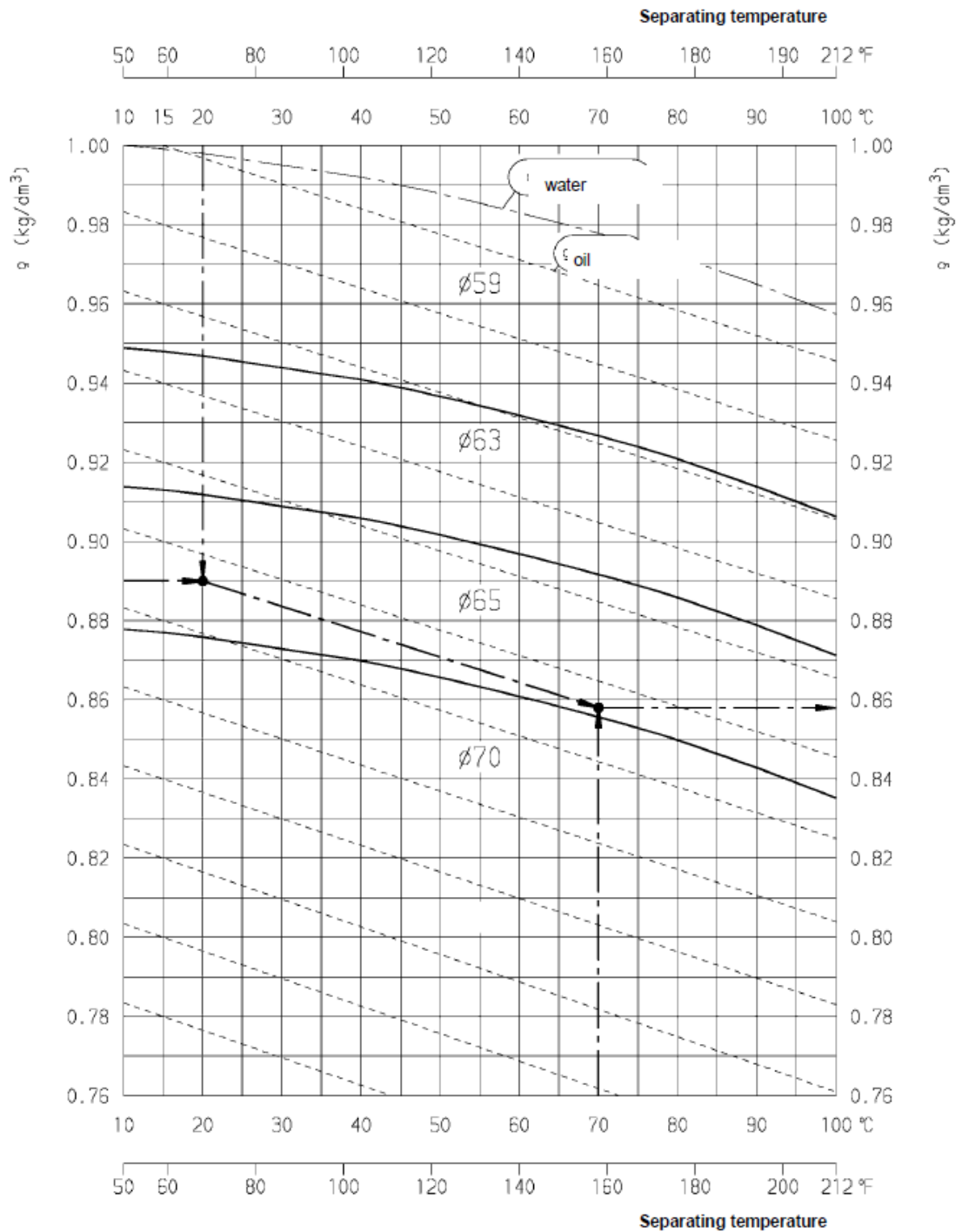
*Figure 34. Diagram used to determine required gravity ring diameter [34]*

Starting point is oil density at 20°C. Line with slope parallel to the other dashed lines is drawn until it intersects vertical line noting temperature at which separation takes place, which is in this case 70 °C. From that point one can draw horizontal line to the right to get oil density at separation temperature.

For those values gravity ring of 65 mm of inner diameter is found. If for some reason gravity ring with such inner diameter is not available, a smaller ring can be machined to the required size and tested before continuous use.

### 4.2.3. Centripetal pump

Separated liquid[27] leaves the bowl space by means of centripetal pump. Its operation principle is opposite to the one of centrifugal pump although they yield same result. In the case of centrifugal pump, fluid is led through centre of rotating impeller. In contact with impeller blades, fluid gains kinetic energy and via guided vanes flows through volute casing where kinetic is converted into pressure energy, so the fluid can overcome all pipe resistances and reach desired location.

On the contrary, centripetal pump impeller is stationary, firmly connected to the hood of the separator. Liquid in the bowl has a lot of kinetic energy because it is influenced by the centrifugal field produces by intense rotation. Spiral channels of centripetal pump, peel off the clean oil so it enters the pump from periphery to the centre. During this path, its kinetic energy is converted so it can be discharged out of separator under pressure.
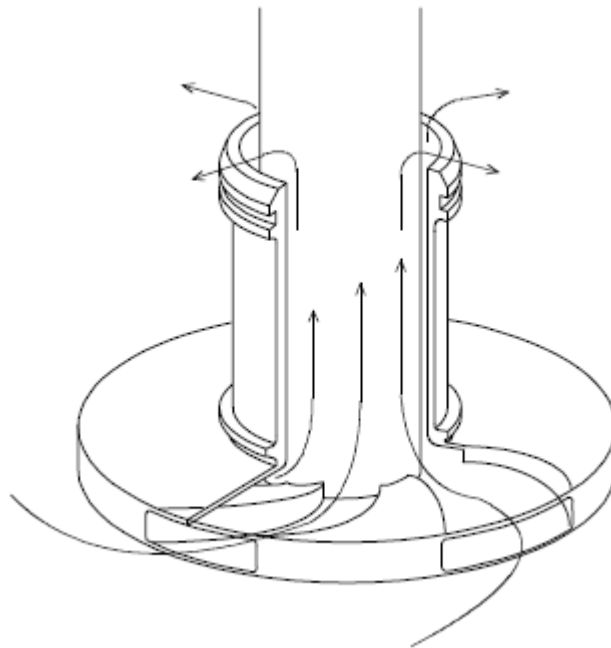


*Figure 35. Centripetal pump [35]*

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[27] In case of marine centrifugal separator, it is either fuel or mineral oil, but in general it can be any liquid which got separated as lighter phase

The immersion depth of centripetal pump in the liquid is low with a small backpressure. It can be increased by throttling the valve in the discharge line. In this way good seal is obtained and the liquid is free of air contact so the foaming will not occur. Moreover, higher backpressure is formed to the clean oil can be properly delivered to the lube oil system or in case of fuel oil, to the fuel oil service tank.

One more pump of such design is also mounted on the top of the separator namely *liquid sensing pump*. Its function is to continuously deliver small sample of clean oil to the *Water Content Monitoring System (WMS)*[28].
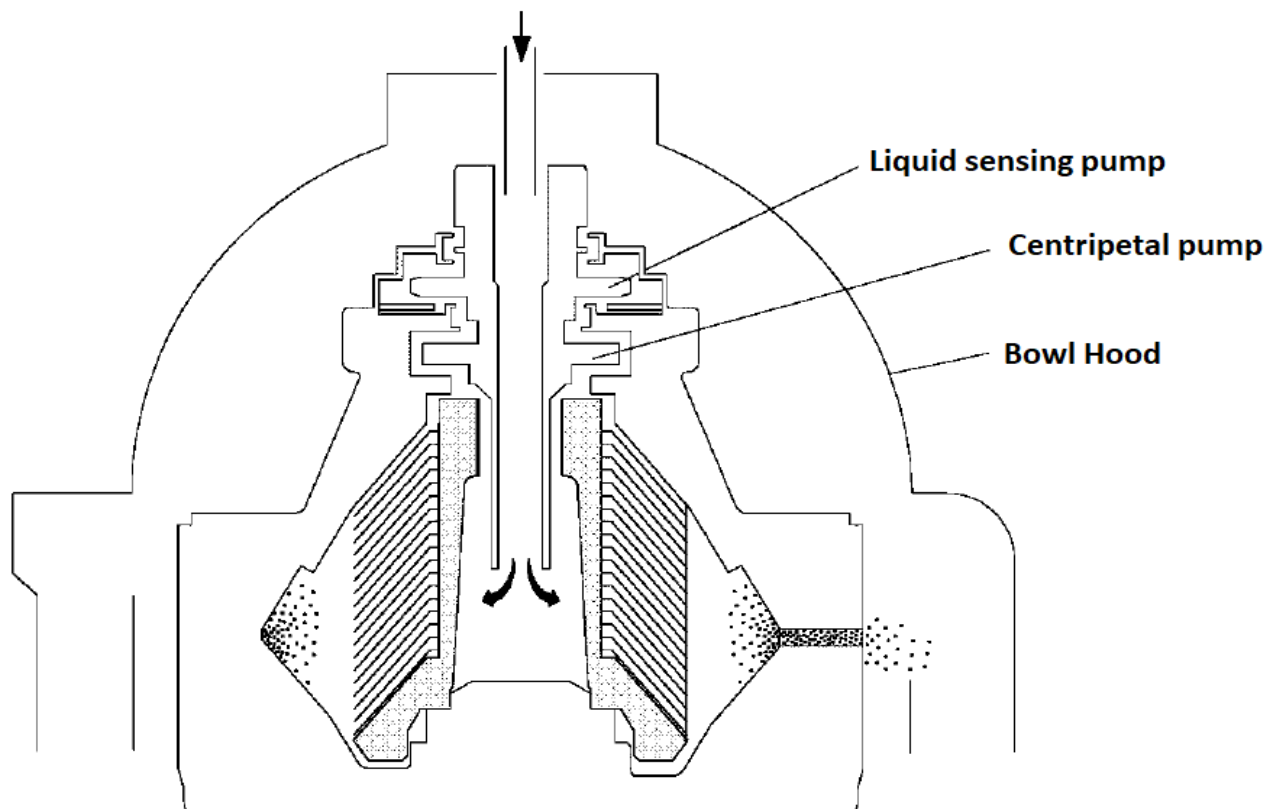


*Figure 36. Position of centripetal and liquid sensing pump [34]*

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[28] This system is used on GEA Westphalia separators which work as clarifiers and purifiers at the same time. Operation of such purifying systems will be presented in chapter 5.

### 4.2.4. Separator capacity

During engine room design, it is necessary to determine the size, i.e., capacity of both lubricating and fuel oil separators.

For diesel engine fuel feed following data is important:

- Type of engine used for propulsion and electricity generation.
- Engine power
- Separation time
- Manner in which oil is separated
- Specific fuel oil consumption and total daily fuel consumption of particular fuel used

For diesel engine lubrication following data is important

- Type of engine used for propulsion and electricity generation
- Engine power
- Separation time
- Engine lubrication and cooling design
- Total oil flow though the separator
- Lubrication pump capacity
- Lubricating system total oil capacity
- Oil type and viscosity
- Number of separation cycles required so that total amount of lubricating oil in the system is separated, per day

For steam turbine lubrication:

- Steam turbine power
- Total oil quantity that fills steam turbine lubricating tank (combined with reductor)
- Time required for separation of the systems total lubricating oil quantity (in hours per day)
- Viscosity and type of lubricating oil used
- Temperature at which lubricating oil is separated
- Number of separation cycles required so that total amount of lubricating oil in the system is separated, per day

Required separator capacity intended for diesel engine used for propulsion is determined according to the recommendation of separator manufacturer. Fundamental physical quantities which are considered when determining separator capacity are maximal engine power and its specific fuel consumption, and are calculated by expression:

$$Q = \frac{P \cdot b \cdot 24}{\rho \cdot T}$$

where: Q – fuel oil flow quantity [m$^3$/h], P – maximal engine power [kW], b – specific fuel oil consumption [kg/kWh], $\rho$ – fuel oil density [kg/m$^3$],T –continuous operation time [h/day]

In order to determine optimum separator capacity, additional 18 % should be added to the specific fuel oil consumption (b) because of water content and impurities that are removed by separation. Based on Q and fuel viscosity most optimal type of fuel separator is chosen from the tables given by manufacturers. Real separator capacity can be larger than the value obtained from equation (1), because it is a function of the viscosity.

Lubricating oil separator capacity is determined according to the following expression:

$$Q = \frac{P \cdot v \cdot z}{t_s}$$

where: $Q$ – optimal real capacity [m$^3$/h],P – diesel engine power [kW],$v$ – lubricating system specific filling [m$^3$/kW]; usually 1.4 m$^3$/kW, $z$ – number of times systems total oil quantity has been separated per day; usually 3    times per day, $t_S$ – hours per day during which separator is in operation; usually 23-24 h/ day

Once the size of purification system is determined and set in operation, its maximal capacity still depends on: viscosity, temperature, density, degree of contamination, water content and the desired degree of purify of the product. [18], [34]

## 4.3 SLUDGE DISCHARGE HYDRAULIC MECHANISM

During the separator operation, sooner or later (depending on the fuel purity) solids will accumulate in sludge space so that interface will be pushed closer to the centre of rotation. Water droplets will start to appear in clean oil outlet, thereby contaminating clean oil. Before implementation of control units in purification systems, engine room crew member had to stop the separator, open it, and manually remove deposits build on bowl walls before separator can be started again. This required time, especially if it was necessary to carry out such operation often, for example due to dirty oil.

With rise of automatization technology, separation process became faster and more efficient. Engine room personnel intervention was no longer needed during everyday operation which allowed them to be focused on other tasks.

Hydraulic mechanism located at the bowl bottom is used to carry out sludge discharge cycle. There are several different versions, but they all employ same hydraulic principles for opening and closing of the bowl.

### 4.3.1. Alfa Laval hydraulic mechanism
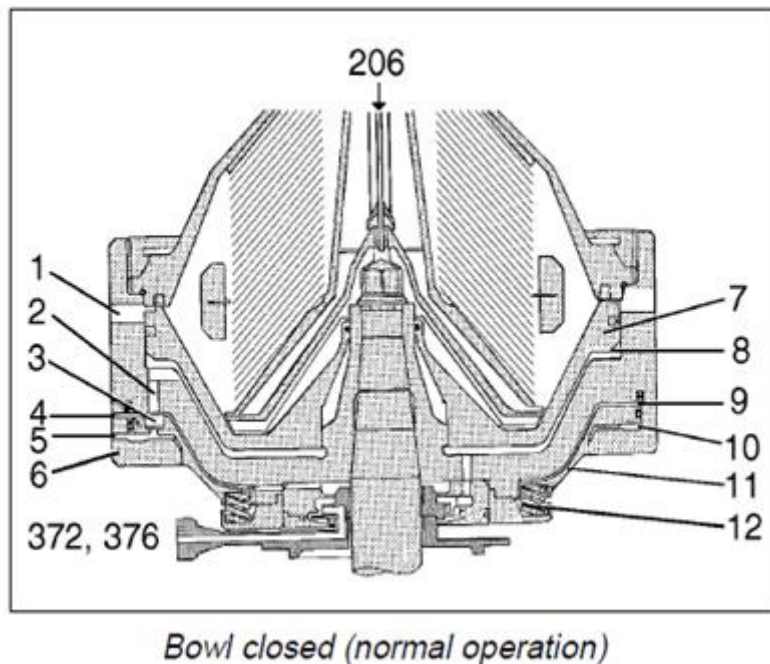


*Figure 37. Bowl hydraulic system during normal separator operation [36]*

1. Sludge port, 2. Drain channel, 3. Drain valve plug, 4. Nozzle*, 5. Nozzle*, 6. Dosing ring*, 7. Sliding bowl bottom*, 8. Closing water space, 9. Opening chamber*, 10. Closing chamber*, 11. Operating slide*, 12. Spring*

206. Displacement/sealing water inlet, 372. Opening water inlet*, 376. Closing and make-up water inlet*, * Parts effecting a sludge discharge

During separation process bowl is closed meaning that outlet holes for sludge discharge are covered by the sliding bowl bottom (7) which is pressed upwards by force of the closing water[29] in the closing water space (8) located under the sliding bowl bottom. Its force is greater than the centrifugal force of the liquid inside the bowl. When the operating slide (11) is pressed upwards by the springs (12) the valve plugs (3) cover the drain channels (2).
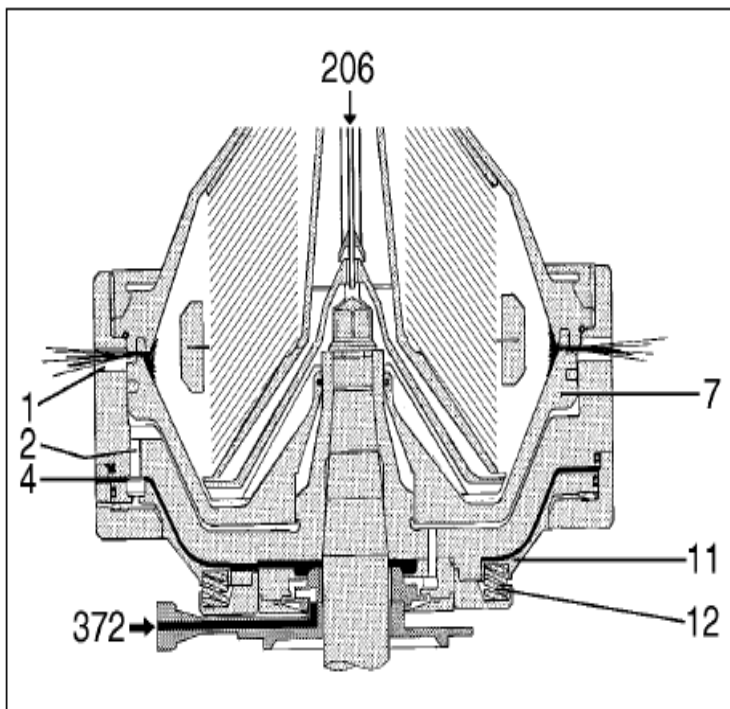


Bowl opens for discharge
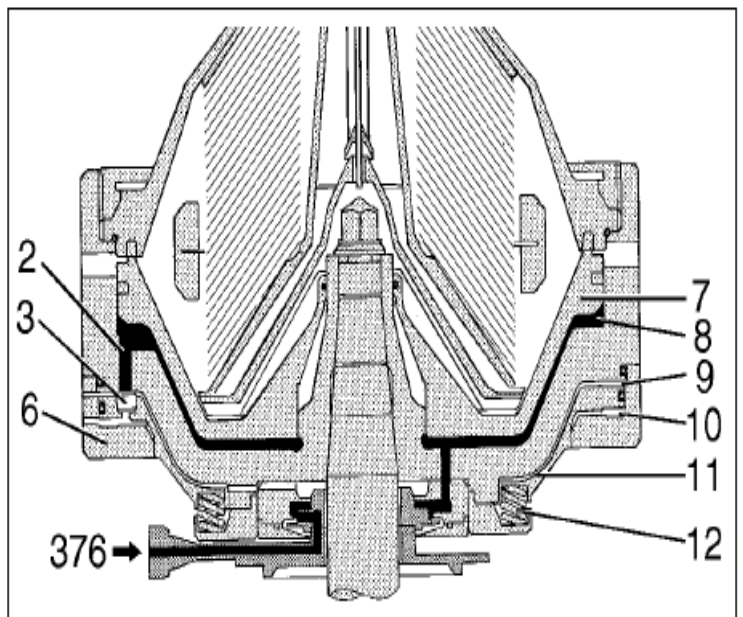
Bowl closes after discharge

*Figure 38. Hydraulic system state during and after discharge [36]*

When the control unit detects water in clean oil outlet, sludge discharge program is initiated. Position of three-way feed valve changes so that oil previously fed into the separator, is now recirculated back to the settling tank.

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[29] Note: *Closing water* is shorter version of term – Operating water for bowl closing and in the same way *opening water* means – operating water for bowl opening.

Alfa Laval L0PX separator bowl has capacity of 13.3 liters, which means that some amount of clean oil remains in the bowl even though oil feed is stopped. It seems like saving it is maybe not worthwhile but during hundredths and thousands of discharge cycles economic benefit that comes from it is significant[30]. In order to avoid such losses, displacement water is led through the inlet (206) prior to discharge so that remaining oil is pushed out of separator bowl through clean oil outlet.

The opening water (372) which is supplied into the space above the operating slide (11), overcomes the force from the springs (12) and the operating slide is pressed downwards. The drain channels (2) open and the closing water drains out through the nozzle (4). This allows the force on the underside of the sliding bowl bottom (7) to become lower than the force on the upper side. The sliding bowl moves downwards, and the bowl opens for a discharge through now uncovered sludge ports.

After some hundredths of a second the opening chamber (9) above the operating slide (11) has been filled by water leaving the closing water space (8). This water overflows through channels situated in the operating slide, down to the closing chamber (10) located between the operating slide and the dosing ring (6). As soon as this chamber has been filled, the hydraulic forces directed up and downwards on the operating slide are equal and the springs (12) moves the operating slide upwards.

The drain channels (2) are closed by the drain valve plugs (3) and the increasing force from the closing water (376) presses the sliding bowl bottom (7) upwards. The bowl closes and the sludge discharge cycle is complete. Bowl closing water is supplied during the sludge discharge sequence and at intervals during the separation sequence to replace evaporated water. [36]

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[30] According to [37] 100 litres of main engine oil costs around 500 dollars. For a separator that can be filled with 10 litres of oil at the time (water seal excluded) and does 12 sludge discharges per day (24 hours), means that it will lose 1200 litres of oil on daily basis. Annual loss caused by full bowl discharge would be around 216 000 US Dollars. Note : 12 sludge discharges per day is taken from Samgong Mitsubishi Operation Manual 2, table 3-10 on page 3-39.

### 4.3.2. Mitsubishi hydraulic mechanism

With Mitsubishi design same results are achieved with slightly different elements. Pilot valve seals the valve seat under centrifugal force while water pressure chamber for closing bowl is filled with operating water. Water surface is kept at certain level by balancing forces of supplied water pressure (upward force) and centrifugally generated pressure of water inside the bowl (downward force). Operating water fills pressure chamber for bowl opening and partially goes through drain nozzle. Once the pressure is sufficient to axially slide pilot valve towards shaft center, valve seal breaks and operating water for closing bowl flows out of the bowl and sludge discharging process begins.

After the process ends, water supply to the pressure chamber for bowl opening is stopped and opening water drains though the nozzle. Spring returns the pilot valve into its original position where it again provides a seal so that closing water pressure can close the bowl thereby allowing process of separation to start again.[38]
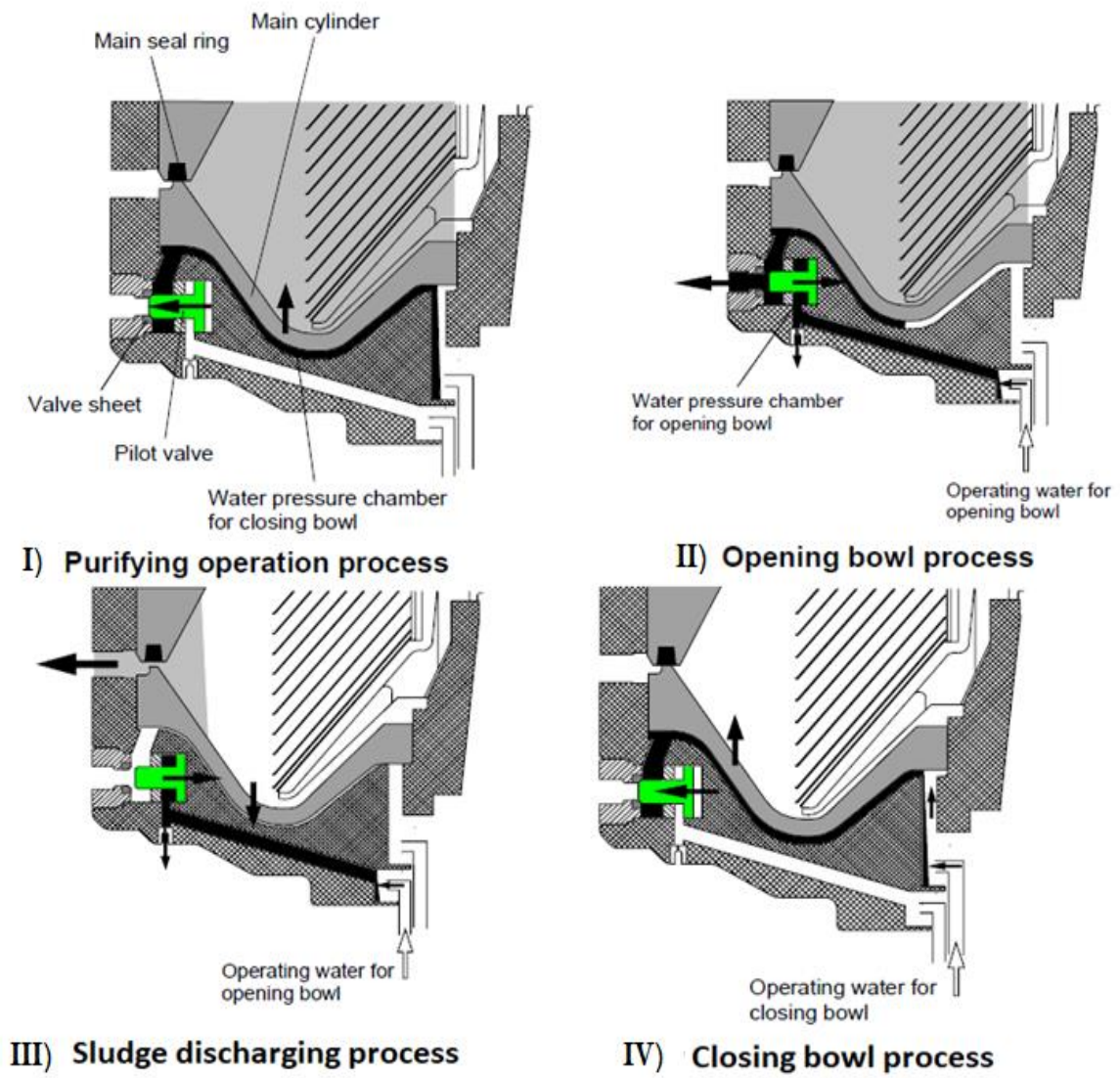
*Figure 39. Mitsubishi bowl hydraulic system [38]*

### 4.3.3. Operating water solenoid valve block

In both designs operating water used for closing and opening of the bowl is supplied from high pressure water system via solenoid valve block.
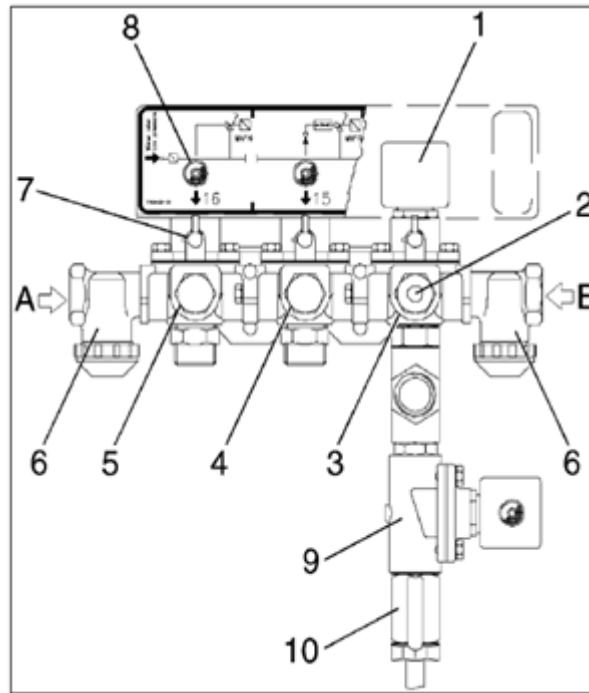


*Figure 40. Water solenoid valve block [39]*

1. Coil, 2. Vacuum breaker, 3,4. Solenoid valve, (constant flow valve included),

5. Solenoid valve, 6. Strainer, 7. Over-ride for manual operation, 8. AC solenoid indicator, 9. Solenoid valve for drain N.O., 10. Manual shut-off valve, A - Water inlet (low pressure), B - Water inlet, high pressure

Water solenoid valve block which receives signal from control unit, supplies water for achieving different functions in a separator. Besides opening and closing of the bowl, displacement, washing and sealing water are also supplied. It consists of four solenoid valves assembled in a block. The solenoid valve (9) is N.O.[31] valve and used for drainage. The two solenoid valves (3) and (4) have a common water supply channel connected to an operating water tank via a strainer (6).

The tank must be installed close to the separators and connected to three separators at most. The height between tank water top level and the separator operating water inlets

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[31] N.O. valve stands for "normally open valve". It is used as safety device to maintain low pressure in the system by allowing fluids to flow during normal operation. Once the coil is energized it closes. Its opposite is N.C. valve – "normally closed valve". It acts as a pressure relief valve and once the coil is energized it opens.

must be at least 2.2 and not more than 3.2. meters. Its function is to supply separator with water and since it is located above the separator, provide static pressure so the bowl is kept closed during normal operation.

A vacuum breaker (2) protects the supply line from negative pressure. The outlet flow is controlled by a constant flow valve and a non-return valve mounted inside the solenoid valves (3) and (4). The solenoid valve (5) is connected to a low-pressure water supply (A) and does not require a constant flow valve and a non-return valve in the valve outlet. A plate that is mounted on the valve block shows the valve functions. Indicator (8) rotates when the solenoid is energized i.e., the valve is open.

The valves (3), (4), and (5) in the common block can be opened and closed manually by pushing and turning the lever (7). When the solenoid is energized, it allows water out through the valve outlet. The indicator (8) rotates. The flow of the outgoing water is determined by the constant flow valve (3) and (4) and is kept constant even at large variations in water supply pressure.

When the control unit switches off the voltage to the solenoid, the diaphragm goes down and closes the valve outlet. The AC indicator (8) stops rotating. The vacuum breaker (2) lets air in if the pressure in the supply line is lower than outside. Its function is to prevent water being sucked in from the valve outlet and polluting the water supply line.

The solenoid valve (9) is used for drain-off water when leakage in valve (3) occurs. When the solenoid valve (3) is open, the drain valve is closed, and water is supplied to the separator. When the solenoid valve (3) closes, the drain valve opens for drainage. The manual shut-off valve at the drain outlet is used only for manual operation of the solenoid valve block. [39]

## 4.4. DRIVE UNIT WITH FRAME

Function of a drive unit is to provide mechanical energy (torque) and its transmission, so the centrifugal field is created inside the bowl. Generally, it consists of primary mover, which is three phase induction motor, connected via clutch to some type of power transmission. Whole system is housed and supported by frame. On following figure driving units from Gea Westphalia and Samgong-Mitsubishi are shown because they use different transmission design.
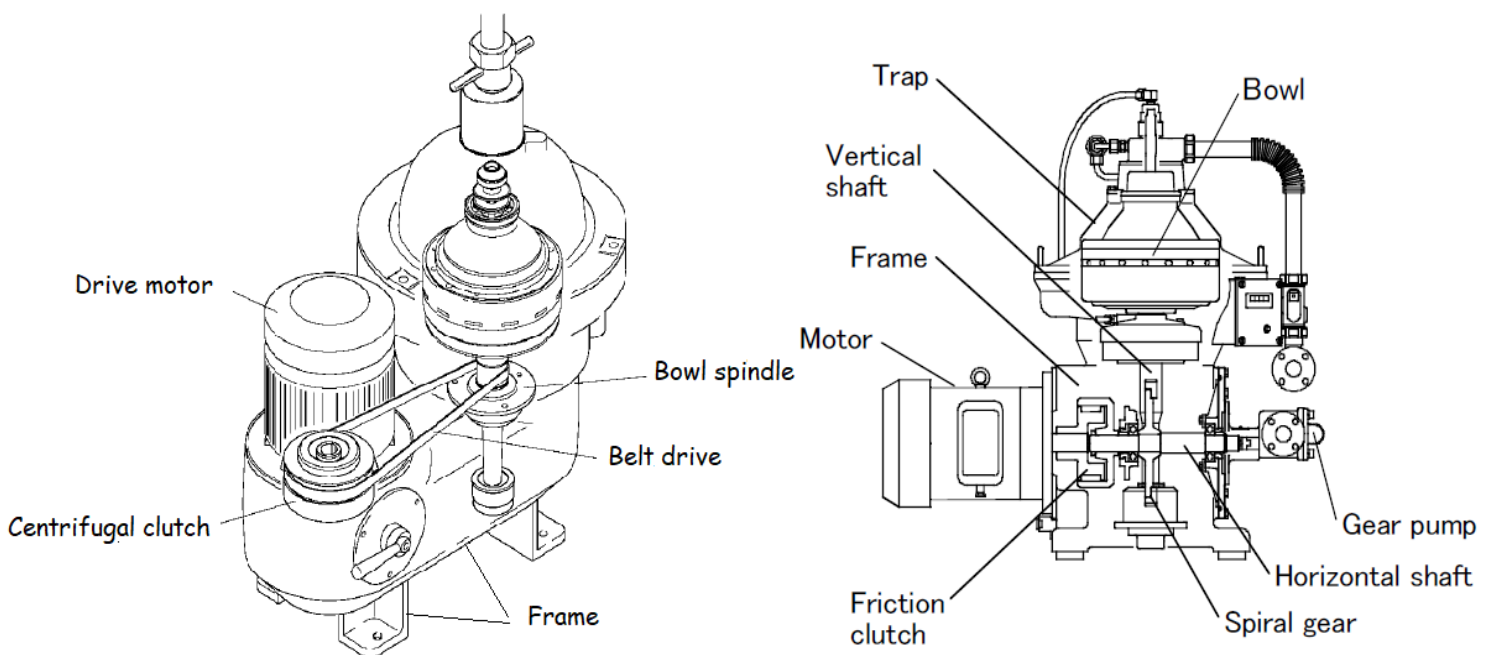


*Figure 41 Drive Unit from Gea Westphalia (left) and Samgong-Mitsubishi (right)*
*[34],[35]*

### 4.4.1. Induction motor (asynchronous motor)

Alternating current induction motor as well as three-phase power system was invented by Serbo-Croatian genius Nikola Tesla. Three-phase alternating current is flowing through equidistantly, radially displaced stator coils thereby producing rotating magnetic field whose direction and force intensity alternate in the same way as the current which produced it.

According to Faradays law of induction such field will induce voltage in short-circuited squirrel cage rotor causing flow of electric current. In such conditions force will act on rotor bars perpendicularly to the direction of electric current and magnetic flux and the rotor will start to rotate.
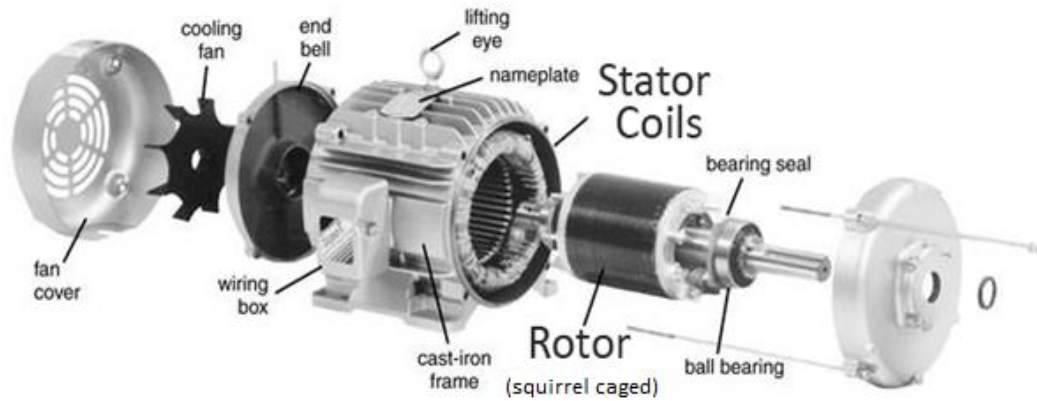


*Figure 42. Induction motor [49]*

### 4.4.1.1. Protection

Electric motors expected lifetime is ensured by means of protection system that prevents motor from following operating conditions: under-voltage, over-voltage, overloading, overheating, short circuit and single phasing[32].

Under-voltage has harmful effects on motor windings because of insufficient torque that is being produced to the load. This results in considerable amount of tear and wear in stator windings as well as decline in efficiency (waste of energy). In case that motor is powered through the contactor then it has built-in under-voltage relay which acts safety element. If motor is powered by means of breaker, then the spring overcomes electromagnetic force in the breaker coil and shuts it down.

Short circuit is most harmful condition for electric motor due to extreme values of electric current that flows through the stator coil. Protection is ensured by implementing fuses or short circuit breakers.

Over-voltage is a state when supply voltage rises above rated. It causes excessive current flow and voltage stresses that damage motors electrical insulation system as well as other motor parts.

Motor is protected by means of relay which shuts it down if such condition is prolonged.

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[32] This is condition where one phase of the motor looses its power supply

Overloading protection also known as bi-metal protection is shown on following figure. Electric motor is powered through breaker, which stays closed until electric circuit that powers its coil is not opened. In latter circuit, there is the bimetal protection contact F1, which opens in case of bimetal overheating[33]. Once it opens, control circuit stops powering main breaker and electric motor turns off. Protection can be designed with manual or automatic reset. Overloading causes excessive heating in stator windings (energy waste) and reduced service life so is therefore unacceptable.
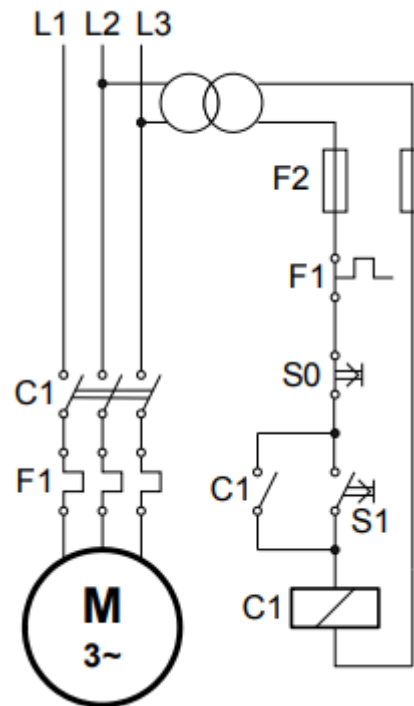


*Figure 43. Bimetal protection [50]*

Overheating has similar negative effects as overloading but with lesser degree. By mounting special termo-probe (PT 100) on the hottest location near stator windings, overheating can be detected in early stages without damage being done.

Single phasing protection is necessary only for motors which are inclined to continue its operation even if power supply to one of the phases is stopped for any reason. In such conditions induction motor loses significant amount of torque therefore revolution number decreases meaning that the slip is increased.

Consequence is increase in stator current that will than trigger overload protection or in more severe case, short circuit protection. [50]

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[33] Sensitivity of protection is determined by the thermal expansion characteristic of bimetal

### 4.4.1.2. Starting

Every starting of induction motor is followed by overload of stator windings. Electromagnetic force is overcoming the inertia of the load which acts as resistance causing large stator current being 5 to 8 times greater than full load current follow by significant voltage drop. Besides, higher torque is required so separator bowl can be accelerated in short time interval[34]. High and unbalanced starting current causes oscillations in power grid, excessive heat in stator windings, as well as vibrations in mechanical parts. In order to avoid potential damaging effects (reduced service life) of such operating conditions, there are many technical solutions which reduce starting current while necessary torque is maintained.
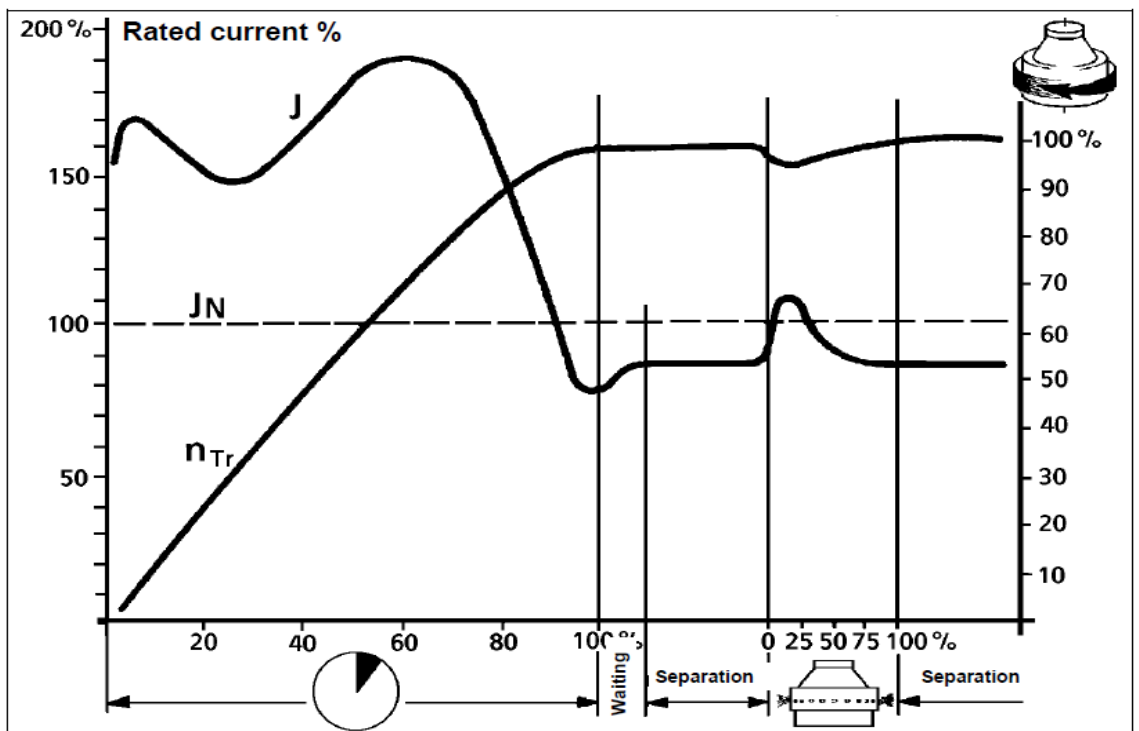


*Figure 44. Start-up diagram Gea Westphalia OSD-18 Separator [34]*

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[34] For example, Samgong-Mitsubishi Selfjector completes start-up sequence in less than 5 minutes while Gea Westphalia OSD 19 Model requires 2 to 4 minutes to reach 3000 rpm (50Hz) or 3600 rpm (60Hz) [34],[35].

### 4.4.2. Starters

Starters are devices whose function is to provide safe, reliable, and technically sufficient start of electric motors. In this chapter few different types will be presented.

*4.4.2.1. Star-Delta Starter*

Its operation principle is based on different ways phases can be connected in motor terminal box resulting in different voltage and current values.
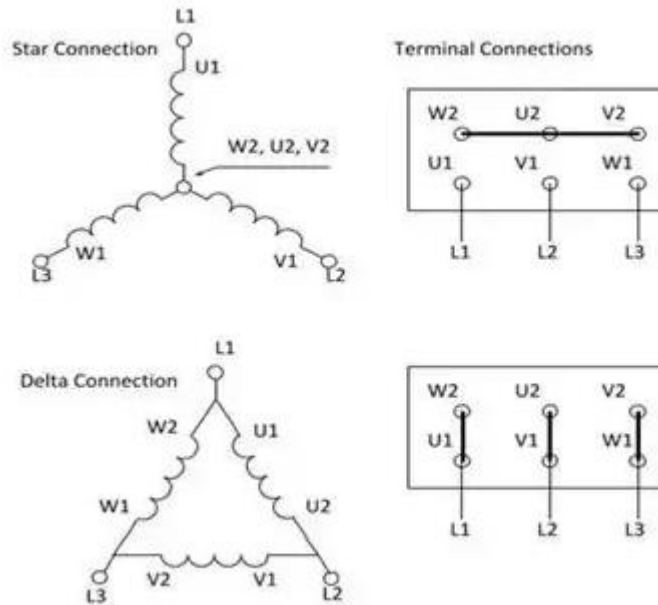


*Figure 45 Star-Delta Connection [41]*

In star connection all three terminals are connected to a common point known as neutral point thus forming a shape that resembles a star symbol. The voltage between ends of one phase and neutral point is √3 times lower than voltage between two lines. This results in phase current being equal to the line current which is √3 times lower than nominal value. Motor power is calculated as product of line current and voltage (P=√3UIcosφ) thus 3 times lower current yields 3 times lower motor power and vice versa.

In delta connection stator windings (phases) are connected in series thus forming triangle shaped closed loop with no neutral point. The line voltage is same as phase voltage resulting in line current being √3 greater than phase current and approximately 3 times greater than line/phase current in star connection.

To give perspective in numbers let line voltage be 400 V. In star connection, phase voltage will be 230 V. If coil impedance is 20 Ω then the value of line and phase current is 11.5 A equally. But with delta configuration line voltage will be equal to phase voltage with line current and phase current having 34.6 and 20 A respectively. [42]

Motor is started in star configuration and after transient period is over it continues to run in delta configuration. Switching between two is achieved by means of two contactors (one for each configuration) and a timer installed in power box.

Although practical and cheap star-delta starter has several disadvantages such as low starting torque which limits its application, requirement of 2 sets of cables from starter to motor, and six terminal box. [40],[43]

### 4.4.2.2. Autotransformer starter

Another solution for dealing with large inrush current when starting induction motor. It can work on motors in both star and delta configuration. Autotransformer is special kind of transformer where energy is partly transmitted via direct electrical connection between primary and secondary coil. This has several advantages such as: smaller cross section of the core (lighter laminated steel core) and lower power losses (higher efficiency). However, their only application in marine electrical grid is for starting induction motors because primary and secondary windings are not electrically separated.

On the following figure, closed transition autotransformer starter wiring diagram is shown. It starts operating on full voltage and later as sufficient motor rpm is reached, autotransformer starter gets removed from the electrical circuit.
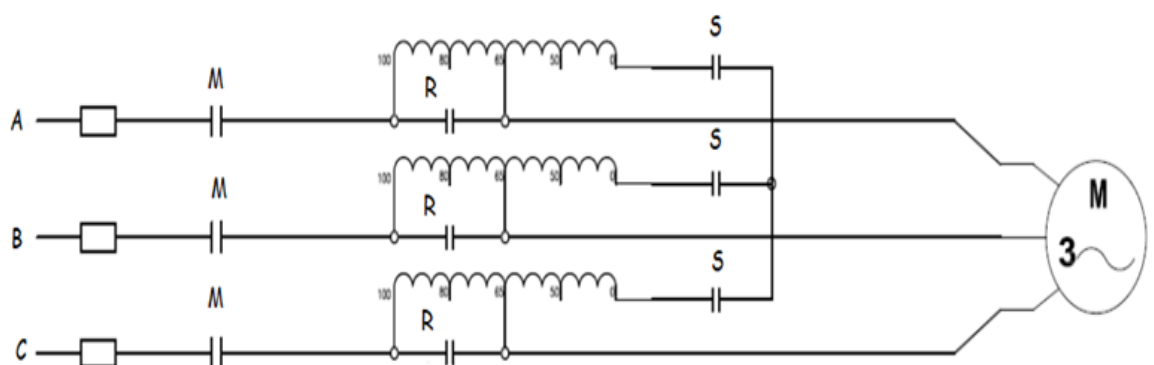


*Figure 46 Closed transition autotransformer starter [44]*

Autotransformer is inserted between the motor and power supply. Voltage at autotransformer primary side is reduced proportionally to the so called "tap"[35] setting of autotransformer which is expressed in percentage (most common values are 50, 65 and 80%).

Motor current is calculated as current which would flow if full voltage is applied, multiplied by tap setting. Due to principles of autotransformer operation, line current and motor torque values decreases even more because they are calculated as a function of tap setting squared. On the figure 46, autotransformer control circuit is shown.
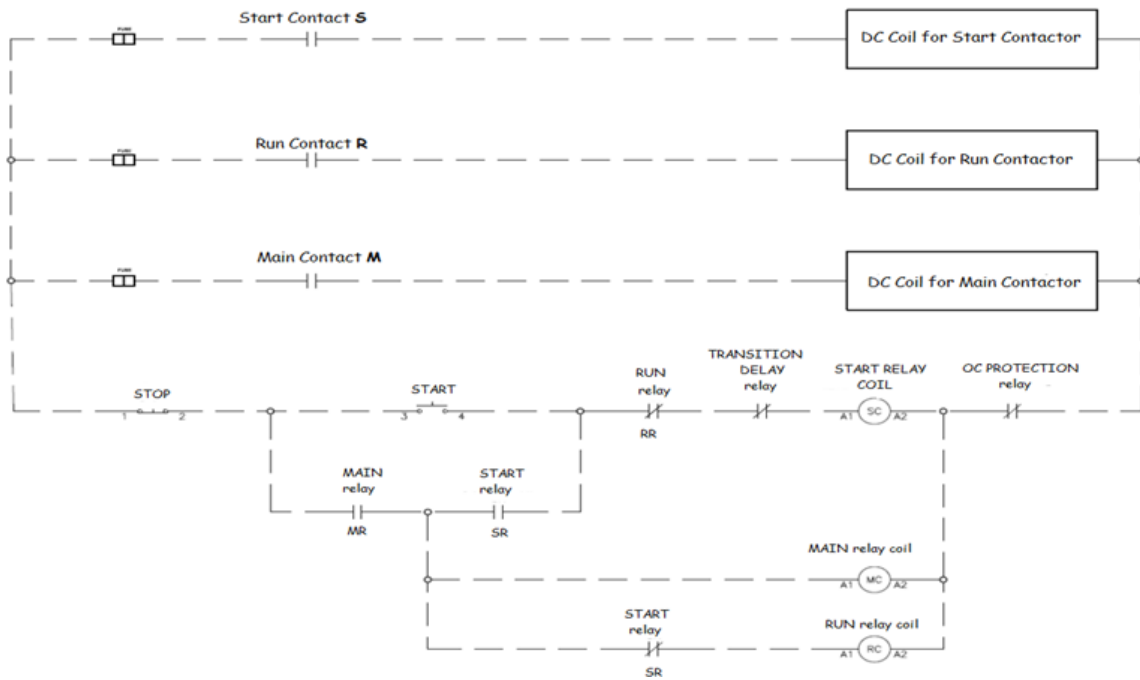


*Figure 47. Autotransformer control circuit [44]*

When the start button is initially pressed start relay coil "SC" gets energised. Consequently, the normally open start relay contact "SR" closes, and main relay coil "MC" energises thereby closing the contact "MR". Result of this sequence is closing of start contactor "S" and main contactor "M" thus connecting the motor to power source which applies reduced voltage across its windings. Motor begins to accelerate and gain speed. At instant when full loaded motor stops to accelerate the transition delay relay will open and deenergise the start relay coil "SC" which opens contact "SR".

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[35] Tap setting refers to the ratio of coil turns between secondary and primary side.

At the moment when the start relay coil is deenergised the autotransformer acts as series reactor until the moment of closing the run contactor "R", meaning that the motor is always connected to the power source and there is no temporary disconnection from the power supply like in case of star-delta starter.

When start relay coil is deenergised, run relay contact "RC" will be powered up thereby closing the "R" contactor. The autotransformer is now disengaged from the power circuit and the motor is fed by full voltage across its windings.

Comparing to other reduced voltage starting methods autotransformer starter provides highest starting torque with lowest starting line current. However major drawback is cost because circuit and switching are complex therefore more expensive.[43], [44]

### 4.4.2.3. Soft Starter

Another widely used device for reducing starting current is soft starter. Its main component is a thyristor which is semiconductor device. With positive impulse applied to thyristor "gate" it opens allowing current flow and closes when the current voltage drops beneath certain threshold. Its main functional property is that flow of electrical power is determined by conduction angle Ө which defines period during which thyristor is switched on.

For each phase of a motor there is 1 pair of antiparallelly connected thyristors. Instead of full sinusoidal voltage, the motor whose start is initiated by soft starter receives decreased voltage due to delay in thyristor firing i.e., smaller conduction angle Ө. As the motor accelerates thyristors fire sooner (delay angle gets smaller), until the motor is fully loaded, and thyristor delay angle becomes 0. [40],[45]
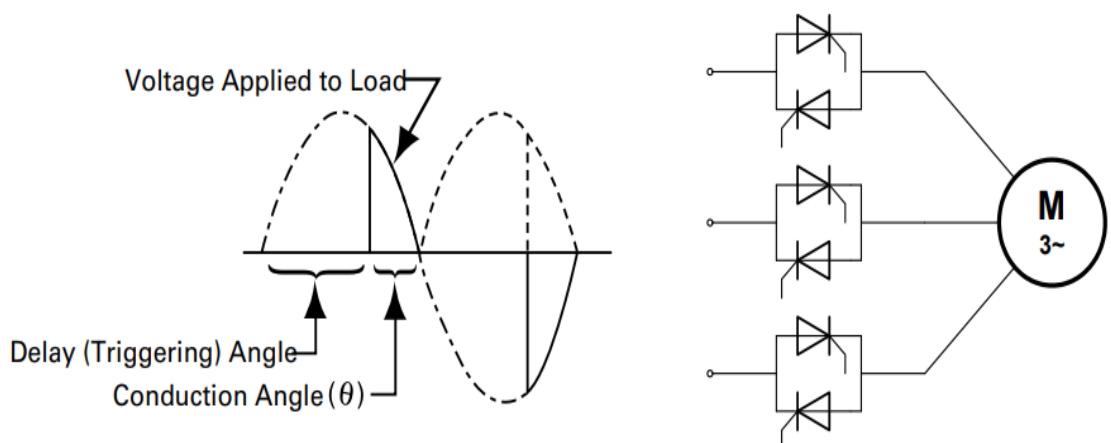


*Figure 48 Thyristor phase angle (left) and Soft starter (right)[40],[45]*

### 4.4.3. Power transmission

Inrush current stress and fluctuations in electrical grid are besides starters reduced by means of a clutch. It enables unloaded motor start and its gradual loading through frictional connection between inner elements.

At the end of the motor shaft, friction boss with a friction clutch elements is fitted. Together they are inserted into friction pully which is depending on the design, connected to the belt or gear drive. Position of clutch shoes (clutch elements) relative to the surface of friction pulley is determined by the balance between spring and centrifugal force. Transmitted mechanical power is proportional to the force pressing clutch shoes, which is in turn function of rpm. The bowl reaches nominal speed because centrifugal force has completely overcome spring force and presses clutch elements fully so that the friction insures complete power transmission.

Separator manufacturers employ belt or gear drive transmission. On the following table advantages and disadvantages of both are shown:

| Gear drive | Belt drive |
|---|---|
| Requires less space | Requires more space |
| Low friction loss therefore higher transmission and more efficiency | High friction loss, therefore lower transmission and less efficiency |
| Less maintenance but with higher costs | High inspection and maintenance that is cheap and convenient |
| Great life expectancy | Low life expectancy |
| Tolerances are very important therefore equipment design is complicated | Easy, flexible equipment design as tolerances are not important |
| No isolation from shock and vibration between driver and driven system | Isolation from shock and vibration between driver and driven system. |
| Requires regular lubrication | Requires relatively less or no lubrication |
| Noisy in operation | Very quiet in operation |

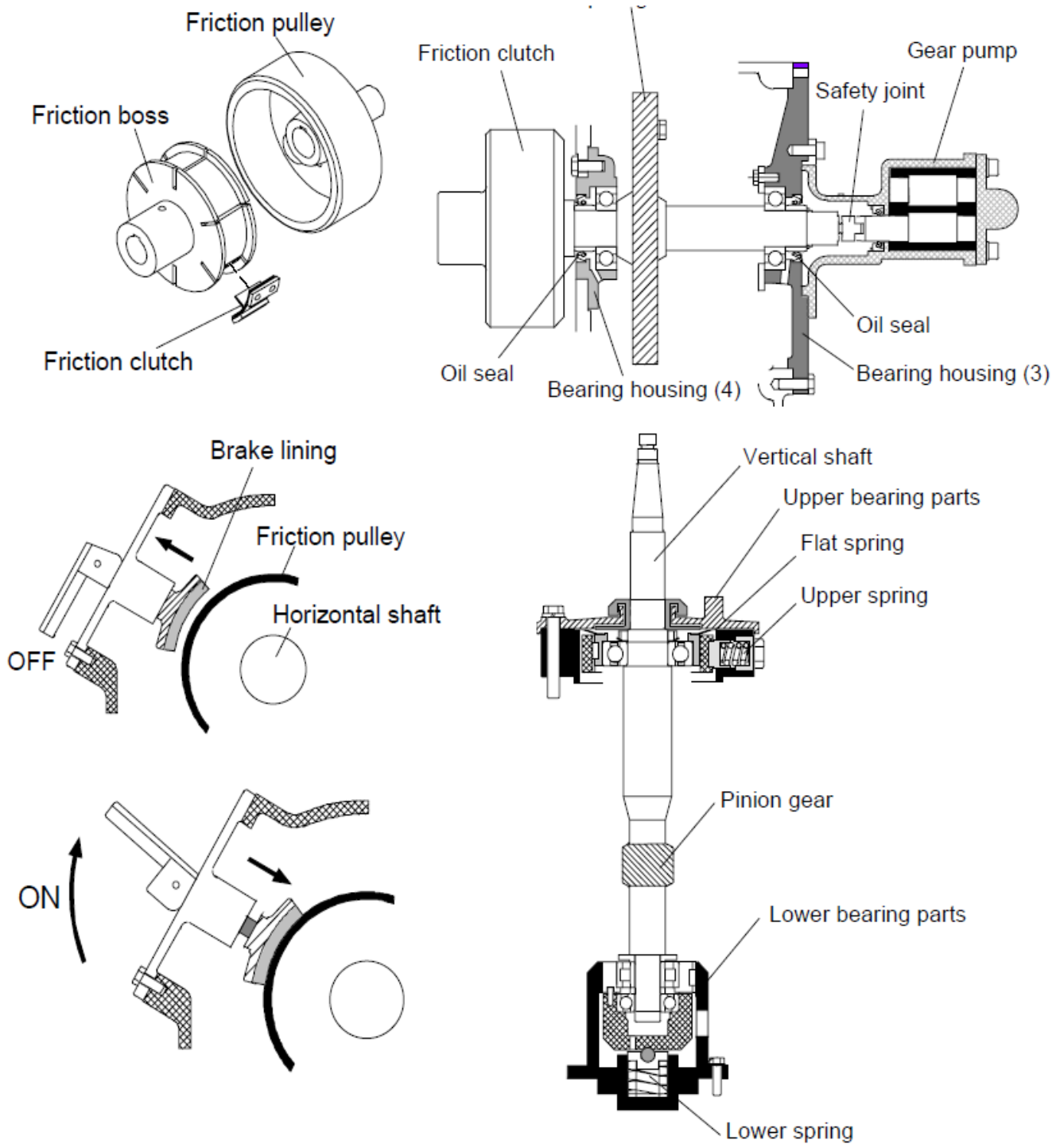*Table 2. Comparison of Belt and Gelt drive characteristics [38]*

*Figure 49 Details of Samgong Mitsubishi gear drive [35]*

Brake handle can be found on the outer side of the frame. It is safety device used to stop the separator if electrical means fail. Every time separator is stopped for inspection or repair brake must be activated. Before separator is started, brake position must be checked.

The bottom of the frame is filled with lubricating oil whose level is checked by visual inspection (once a week) through sight glass. Mechanically driven gear pump sucks oil and displaces it through the bores of the shafts to the bearings and gears. Outer parts of mechanical drive are splash lubricated from central oil bath. Manufacturers recommend complete oil change after 6 months (4000 h) in case of mineral oil or 1 year (8000 h) if synthetic oil is used.

In some designs[36] shafts are also used for supplying closing water to the bowl hydraulic device. Besides the electric motor, maximum revolution number is determined by gear ratio of the drive, or the diameter ratio of pulleys. [35]

## 4.5 CONTROL SYSTEM

First two part of this chapter presents control system from theoretical standpoint where basic terminology and concepts are explained. Last part of this chapter is focused more on practical knowledge and data.

### 4.5.1. Context and background

During the second half of 19. Century, second industrial revolution was starting to take its swing, with more and more resources were invested in engineering and related sciences. One of the major discoveries of that period was new physical quantity called entropy. With it came the knowledge about the "ultimate fate" of every system that uses energy, namely that in absence of any input (energy), the system will inevitably reach the state of maximum entropy and thus seize to operate at all. In other words, if any system set in operation is to achieve and continually produce desired goals, it must be controlled.

Before the development of control engineering, majority of systems had to be controlled and supervised by engine room crew. For example, marine disk-stack separators had to be manually stopped and started every time so the new separation cycle can take place. Sludge accumulated on the bowl walls had to be manually removed and oil heater temperature manually set. These and many more examples point to the fact how much everyday operation relied on engine room crew.

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[36] For example Alfa Laval MSPX 303 TPGP-61

As the control engineering/ automation were being developed and implemented, more complex systems could be controlled with less attention from human personnel. This resulted in larger initial investments due to control equipment cost, but with many great advantages such as: increased system efficiency, unattended operation (reduction of human resources), control of complex system which would otherwise be impossible[37].

### 4.5.2. Introduction to control systems

Control systems can be grouped based on type of loop they employ, namely on *open* and *close* loop control systems. They are presented in block diagram where rectangles are used to define sub-components of control system and the arrows represent signal flow.

With open loop control, signal flows in only one direction meaning that the process output is not used for control action. Initial command is fed as input to process in question with expectation that the system will reach to desired state. Simple example of such category would be actions that are initiated by timer. In case of separator, sludge discharge command can be programmed so that every hour one takes place, regardless of bowl wall state[38]. Open loop design has several advantages such as: low equipment cost, fast response action, easy implementation, and good stability under normal conditions without disturbances.

However, its application is limited because of the complexity of many technical processes. Control of such processes requires feedback loop (close loop control) so information about the process state can be used for adjusting controller input thereby achieving superior control. What is missing in open loop control is comparison between reference value and process output. By comparing these two values, difference between current state and desired state (error) can be measured and thus corrected, keeping process stable and driving towards desired state.

There are many advantages such as: system that is inherently unstable can become stable, wider range of systems states becomes available, outer disturbances can be nullified, system is easy to calibrate, and optimisation can be better implemented.

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[37] One can imagine the difficulty of manual boiler water level control on a steam-turbine vessel which is maneuvering in the port.

[38] This example is not general because separations systems like ALCAP (Alfa Laval) or UNITROL (Gea Westphalia) use sensors to determine if sludge discharge is required or not. Principles of such systems will be presented in chapter 5.

For example, oil heater temperature control requires close loop, especially in dynamic working conditions (constant fluctuations in oil flow rate). The amount of steam which is used as input is in direct relationship to the current oil temperature (output).

However, there are few disadvantages of closed loop system. Depending on the circumstances and the nature of the system it can become unstable due to effects of closed loop. Since the system is more complex, probability of any fault occurrence is greater. Complexity makes system expensive, and if technology standards are high, maintenance cost will also be greater.

There are also certain limitations positive effects can have on the system that is close loop controlled. They are not consequence of controller design but are imposed by hardware that is implemented in control loop. Examples of these is: so-called "dead time"[39], sensing device limitations (noise, inaccuracy, signal delay), actuator limitations (friction, clearances, elasticity).



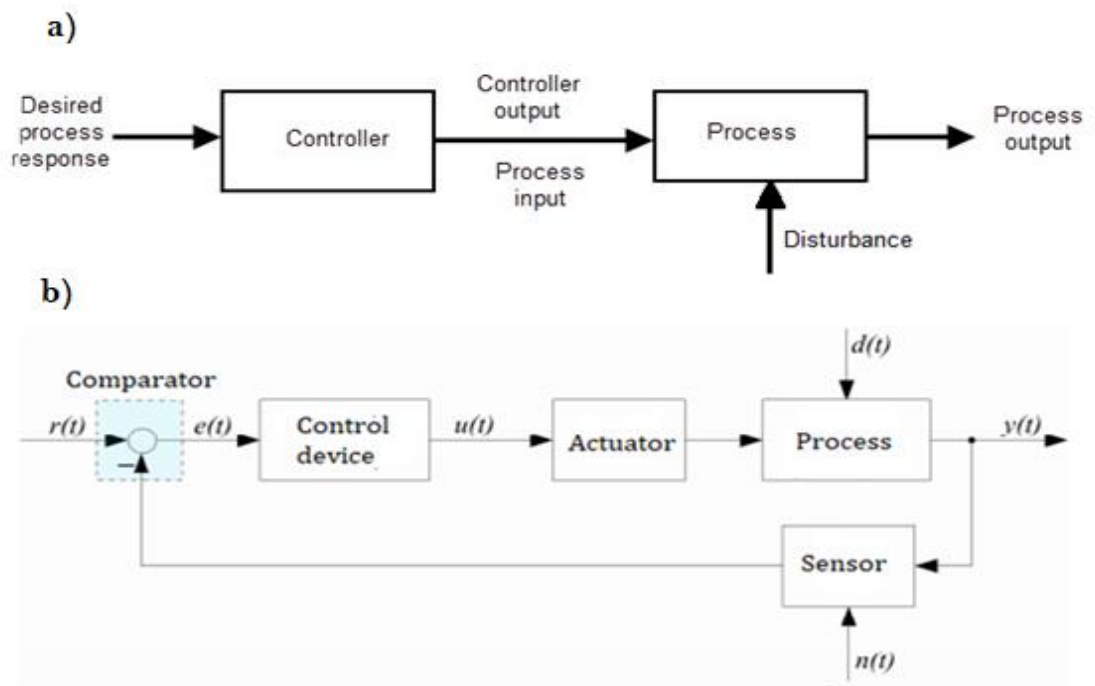*Figure 50 Block scheme of open loop (a) and closed loop automatic regulation (b) [47]*

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[39] It refers to the time delay between the moment controller output signal is sent and the moment when measured process variable first begins to respond

Relating to the figure 50:

- *r(t)* - *reference input* is applied to the comparator[40] and represents desired (ideal) behavior of the process variable
- *y(t)* – *controlled variable/output* is process variable that is being controlled
- *e(t)* – *error signal* is the difference between reference input and output variable
- *u(t)* – *control signal/manipulated variable* is the signal that represents controller output and process input
- *n(t)* – *measuring noise* is an error that occur during measuring process and is practically always present. Goal is reducing it to the lowest acceptable limit.
- *Controller* – part of the automatic control system which generates control signal which will act as input to the system that is being controlled. Fundamentally it consists of amplifier and comparator that operate in certain time frame. Broadly speaking it also includes reference value generator and elements for signal processing (e.g. filters, analog/digital converters)
- *Process* – system, subsystem or process whose value (or values) are object of control
- *Comparator* – element of the control system where difference between refence value and output value is calculated and sent to controller so that control signal can be adjusted accordingly. Its operation makes feedback negative[41] thus keeping the process stable.
- *Actuator* - supplies the process with power or material so the latter can be controlled. Example: remote control valves, electric motors
- *Sensor* – besides sensing device, it contains transducer whose function is to convert measured variable into signal that can be processed by controller.

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[41] Positive feedback is almost never used because its effect is completely opposite to that of negative feedback. However, there are a few exceptions where positive feedback has its application, for example audio signal amplifier – patent from E.H. Armstrong (1917.)

Two important terms in control theory are *disturbance rejection* and *tracking control*. They refer to time variability of reference value (*r*) which is termed *setpoint* if it is approximately time invariant and control – disturbance rejection. If refence value changes continuously control is termed tracking control. In that case primary goal of control is that process variable follows reference value.

Main requirements of every control system independent of application are: stability (or relative stability), acceptable response speed, allowed control error (precision) and robustness. Analysis of control systems, depending on its utility takes place in two domains, namely *time* and *frequency* domain.[47]

### 4.5.3. Control Unit (PLC)

*4.5.3.1. General characteristics*

PLC stands for "programmable logic controller" and is term used to describe commercially and industriously applied computer. Historically PLC appeared as a replacement for panels of relays which were used to control technical processes. Using relays for logic operations was time consuming and challenging. Making change in logic or operation of a machine was almost as complicated as staring over with new one. Relays fail more frequently than computer components, so relay logic required more downtime to keep it running comparing to newer PLC based controls. Another disadvantage of relays is that they use more energy and occupy bigger space.

PLC shares many features with personal computer (PC) but can withstand rough industrial environments[42] and perform discrete and continuous operations that PC cannot do. Basic structure incudes input module, central processing unit (CPU), output module and data transfer hardware for programing.

CPU is microprocessor system that contains system memory and processes various pieces of logic. It monitors inputs, outputs, intermediate variables and executes decisions based on instructions located in program memory. Memory also stores data representing conditions of all field devices, and contains the data telling all output field devices what to do.

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[42] Few examples are : high temperature, wet, dry and dusty conditions.

Type of input as well as output module depends on type of signal, namely analog or digital. Analog signals are denoted by sinusoidal waves where information is represented in a continuous range of values. Their bandwidth is low, and hardware never offers flexible implementation. On the other hand, digital signals are time varying with information being represented as a sequence of square waves i.e., discrete binary values (0 and 1). Digital signals have higher bandwidth meaning that amount of data that can be transferred in unit of time is higher comparing to analog signal. Also, their advantage is flexibility of hardware implementation.

PLC operation always follows the same pattern, also known as *PLC scan*. It starts with reading input status. When this phase is over PLC can start to execute programs. During that period processor carries out diagnostics and communication tasks. Finally, processor sets new values to outputs and completes the cycle that is iterated while PLC is in active mode (RUN). Time that is required to complete the cycle depends on the program size, number of inputs and outputs and magnitude of communication activity.
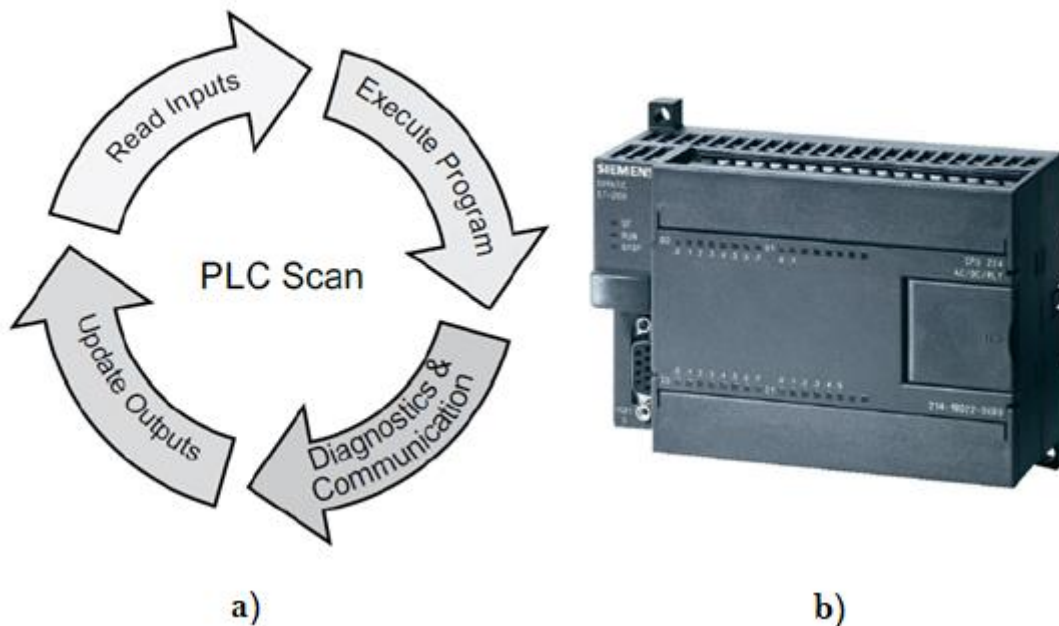


*Figure 51. PLC Scan program (a), PLC Siemens S7-200 (b) [51]*

### 4.5.3.2. Samgong-Mitsubishi controller

Control unit is used within a separation system for automatic control of the separation process. The unit is microprocessor based and comprises output functions for control of ancillary equipment and input functions for monitoring and alarm.

General requirement for control units is that they are programable, so to suit different separator systems and different operating conditions. Control unit interface makes programming easily adjusted to new conditions or new experience.

Sequences that controlled are starting, separation, sludge discharge and stopping. Monitoring is achieved by means of input signals from sensors, and an alarm is given if the preset values are exceeded. Control unit can also have built in temperature controller which operates steam or electric heater. Depending on the requirements for performance it is usually PI or PID controller. Sometimes temperature control is integrated into one main controller for complete separator control.

Programming is made by setting parameters such as: type of equipment, temperature limits, timers for all sequences, etc. Some parameters are set at installation whilst process parameters are easily accessible for adjustment during operation. Programming should be carried out only by authorized personnel because damage to equipment and wrong system control are possible if not done properly. In most cases laptop is connected to control device using ethernet cable and programming achieved by means of application[43].

Control panel is composed of a separator controller (KT-PFC-A), panel box, switches and power supply. On the following figure electric architecture of controller that is located inside control box is shown. It is manufactured by Samgong Mitsubishi and used for controlling GBC-1 type of separator.

Controller can be further divided into four sections. Main Module contains display connected to CPU module and input/output board. Mounted on the same backplate are also Terminal Block Module (T/B Module) and AC 100/220 V Power supply.

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[43] Each manufacturer uses their own software for programming, for example E.G. Studio 5000 (Allen Bradly) and SIMA S7 (Siemens).
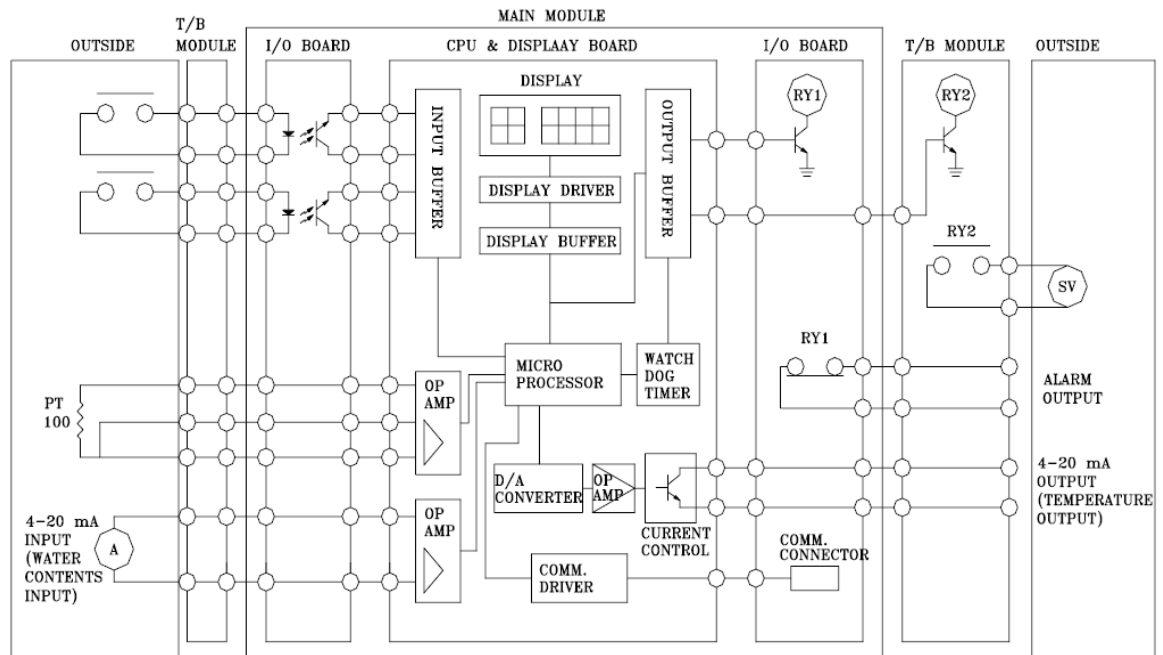
*Figure 52. KT-PFC-A Controller [52]*

Relating to the figure above a few abbreviations and elements will be shortly described. *PT 100* refers to temperature sensor that monitors oil temperature. *Buffers* and *drivers* provide little or no added functionality to the circuit but instead replicate their input at their output with different attributes. They can have many functions, one of which is providing interface between two sub circuits. Even though these types of buffers mostly handle digital signals, they are operating in the real, analog world of voltage, time, current and failures. As such they are analog circuits used to handle real-world (digital) signals.[53]

*OP AMP* stands for *Operational Amplifier* which is linear device that almost perfectly amplifies direct current voltage and are used extensively in signal conditioning, filtering or for performing mathematical operations such as addition, subtraction, integration and differentiation. They are used in combination with external feedback components such as resistors and capacitors that are located between its output and input terminals. By virtue of different feedback configurations, amplifier can perform a diverse number of operations. [54]

*RY* is an abbreviation for *Relay output* and *SV* for *Solenoid valve*. *Watchdog timer* is a circuit external to the processor whose function is to reset microcontroller after certain time expires.

In order to prevent watchdog timers system reset there is timer restart instruction which constantly resets watchdog timer. In case of faulty operation, restart instruction will not be executed, and watchdog will reset the system, thereby protecting it from failures and damage. It can be seen as safeguard of the system. [55]

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Samgong control unit has 8bit Micro Computer with program memory of 8 kilobytes. Data memory contains two different units namely, RAM and EEPROM. Former stands for "Random Access Memory" and is type od temporal memory that contains data which is currently being used, which might be used by CPU and data that can be saved in permanent memory. On this type of memory data is written and read fast so the programs can be efficiently executed. It is volatile meaning that once the current is switched off, RAM loses its data.

EEPROM is a type of ROM memory and is an abbreviation for "Electrically Erasable Programmable Read-Only Memory". Its main characteristic is non-volatility that is, data stored will not be lost once power is switched off. Data is easily read and programmed but it takes more time to write new data on the memory chip. High voltage is used to erase data that it contains. [56]

Control box where PLC is located must be made in such a way to ensure safety during operation in explosion-hazarded areas. Standard *EN 50018* requires flameproof enclosure "d" which states that the housing must withstand pressure and temperature of an explosion of explosive mixture and prevent its transfer to the surrounding atmosphere in case of ignition of explosive mixture inside the housing. Standard *EN 50019* that is type of protection "e" requires additional measures that are implemented that prevent the possibility of inadmissibly high temperatures and occurrence of sparks and arcs in the inside or at the outside of components of electrical apparatus which do not otherwise occur in normal operation. Standard *EN50020* is a type of protection "i". Apparatus built by that standard contains only intrinsically safe circuits, meaning that no spark or thermal effect that can occur during normal operation and certain error conditions, can cause ignition of a certain explosive atmosphere.

### 4.5.3.3. PID Temperature control

Oil heater and steam regulating valve were already presented in chapter 4.1. Supply system. These two combined with temperature controller are used to keep oil at the temperature where optimal separation effect is achieved. PID control can be installed as a program in PLC or have independent controller that only regulates oil temperature. Sensor used in control loop that is used as input to the PLC is usually PT 100 probe. In this section focus will be on basic understanding of PID control, and the role that each term has.

PID abbreviation is used to denote its three constituent control terms namely, proportional (P), integral (I) and derivative (D). Their combination yields a controller that has acceptable quality of response, meaning that it will be fast and accurate with oscillations that are within tolerable limit. Three members can be positioned in multiple ways where parallel relation is most simple one. Parallel PID regulator output is a result of adding proportional, integral and derivative member operation and is expressed by following equation:

$$u(t) = K_p e(t) + \frac{K_p}{T_i} \int_{t_0}^{t} e(t)dt + K_p T_d \frac{de(t)}{d(t)}$$

$K_p$ is a proportional gain factor, $T_d$ derivative time (derivation time constant), and $T_i$ integration time constant. Product $K_p T_d$ is an amplifier of derivative action and $K_p/T_i$ is an amplifier of integration action. Other members as denoted as described on pages 74 and 75. PID regulator transfer function[44] is given by expression:

$$G_{PID} = K_p(1 + \frac{1}{T_i s} + T_d s)$$

Proportional response (P) is only dependent on the difference the reference value[45] (*r*) and process variable (*y*), known as the error term (*e*). Large error will depending on the produce large response whose exact value is determined by $K_p$. So for example if error term has a magnitude of 15, a $K_p$ that is 5 would yield a proportional response of 50. Generally control systems response speed is increased by raising value of proportional gain but this comes with side effects like oscillations which decrease systems stability.

Integral response (I) is applied to solve residual error that is left after proportional control has been applied. Error term is constantly being accumulated so even if the error was small, over time it grows to such extend that it can be easily eliminated. Once the error is corrected, the integral term will stop growing, or in other words, the function of integral response is to drive steady state error to zero.

Derivative response (D) is proportional to the rate of change of the process variable, in this case oil temperature. That causes the output (position of steam regulating valve) to decrease if the process variable is increasing rapidly.

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[44] Transfer function is important concept in control theory that is defined as the ratio of the output of a system to the input of a system. Denotes as "*s*" is a transfer function variable in frequency domain.

[45] Also known as "set point"

Derivative response is adjusted by changing the value of derivative time ($T_d$). In case it is increased, control system will react more strongly to the fluctuations of error term thereby increasing the speed of overall control systems response. In most control systems $T_d$ is very small because derivative response is highly sensitive to noise that can affect process variable signal. Such state combined with slow control loop rate can make control system unstable.

On the following figure PID temperature controller response is shown while HFO separator was put into operation. From the moment oil heater was put into operation until the temperature setpoint of 98°C was reached with negligible deviation, 5 minutes and 20 seconds elapsed. $K_p$ value is set 12 with $T_d$ and $T_i$ being 3 and 60 seconds, respectively. Blue line represents set point value, pink line the output signal i.e., position of steam regulating valve and brown line represents measured signal, that is current oil temperature (process variable).

The moment oil heater is started , position of steam regulating valve is constantly increasing until it reaches maximum opened position. Still the oil temperature is not rising. Approximately after one minute in fully open position, oil temperature starts to rise and controller immediately sends output signal for steam valve closing. Then as the slope of the brown curve starts to decrease, steam flow starts to increase again. This interaction continues for next two and a half minutes until setpoint temperature is reached and oil temperature stabilized.[57],[58]
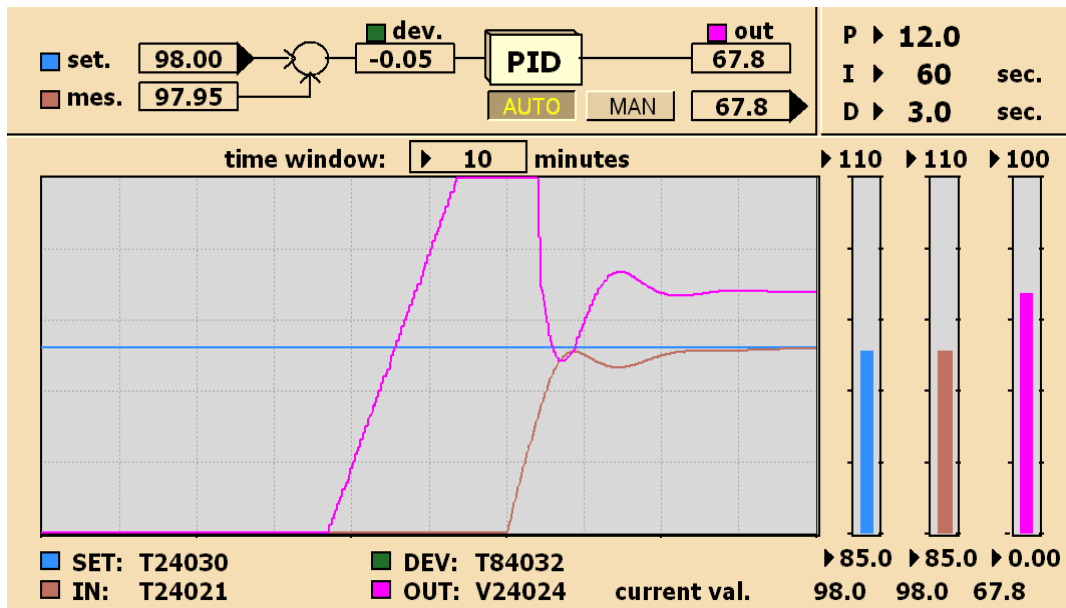
*Figure 53. PID temperature regulator response [28]*

### 4.5.3.4. Timers and Counters

Today's timers and counters are part of PLC software are used to count or time separator process events so that automatic operation can be effectively carried out. They are in principle same device, but they differ in type of value they are counting. Besides software timers/counters there are also mechanical, electromechanical, or electronic timers/counters.

Timers count units of time (seconds) from 0 to some pre-defined value or vice versa. Once it expires or reaches certain value, a control signal is automatically issued to the actuator[46]. Counters on the other hand count how many times has certain process been executed. They can be important not only because they facilitate control but also because such information provides knowledge about state of monitored process.

The times and counts that are set vary with following factors: model of the separator, type of oil feed, operating and sealing water pressure. Therefore, it is necessary to set the timers to match the field conditions.

In the following table timer numbers and uses are listed for Samgong Mitsubishi separator.[47]

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[46] Term "actuator" is general and used to describe any device that take executes commands from control unit in order to control process variable/s. Device that fits into this category has already been presented in chapter 4.3.3. More details and examples in chapter 4.5.5.

[47] There are also incorporated timers/counters that are employed on the separators that are purifier and clarifier in one device such as ALCAP, Samgong GSH-1 Hiddens or Gea Westphalia UNITROL system.

Timer Numbers and Uses

| Timer NO. | Use | Set time [48] | |
|---|---|---|---|
| T000 | Operation intervals of each solenoid valve | 15-20 s | |
| T001 | Bowl opening time (Total discharge) | 3 s | |
| T002 | Replacement water supply line (Total discharge) | 5-32 s | |
| T003 | Sealing water (regulating water) supply time (Total discharge) | 9-27 s | |
| T004 | Bowl washing water supply time | L.O. | 12-47 s |
| | | F.O. | 0 s |
| T011 | Bowl opening time (Partial discharge) | 0.6 s | |
| T012 | Replacement water supply time (Partial discharge) | 2-6 s | |
| T013 | Sealing water (regulating water) supply time (Partial discharge) | L.O. | 1-5 s |
| | | F.O. | 0 s |
| C014 | Intermittent bowl closing water supply intervals | 15 min | |
| C015 | Sludge discharge intervals | Refer to table 3 | |
| T016 | Operating water supply for closing bowl | 5 s | |
| C022 | MONITORING TIME | 20 min | |
| C026 | Water detection count reset time | 30 min | |
| Counter N.O. | Counter Numbers and Uses | Counter | |
| C023 | Bowl washing counter | L.O. | 6 |
| | | F.O. | 0 |
| C027 | Water detection count | 6 | |

*Table 2. Timer/Counter numbers and function [59]*

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[48] Set time format (x- y) means that particular timer or counter is set between listed values depending on the model of the separator.

| F.O. | | L.O. | |
|---|---|---|---|
| F.O. | F.O. (380 mm²/s at 50°C) | Cross-head engine | Trunk piston engine |
| 120 min | 60 min | 120 min | 60 min |

*Table 3. Standard sludge discharge intervals [59]*

Setting appropriate values for timers and necessary adjustments are done during test run by the personnel of the company that manufactured the separator. However, if the field conditions change then the authorized person of the engine room crew must meet new conditions with respecting change in timer and counter settings. [59]

### 4.5.4. Sensors

Sensors are devices with function of detecting changes in its environment by measuring specific physical quantity and transforming that information into signal that is sent to the control unit. For control of separation process different types of sensors are mounted on specific locations thereby enabling process monitoring. Following list of sensors refers to Alfa Laval LOPX separator.

- Temperature transmitter – Measures oil temperature
- Water transducer[49] – Measures the changes of water content in the separated oil
- Flow indicator – Display the oil flow rate[50]
- High pressure switch – Senses high pressure in the oil outlet
- Low pressure switch – Senses low pressure in the oil outlet
- Pressure gauge[51]

---

[49] It consists of two pipes (one inside the other) that are insulated from each other and an oscillator, thus forming a circular capacitor. It is located in the oil outlet. Oscillator converts DC into high frequency AC that is fed to the capacitor whose capacitance depends on the dielectric constant of the liquid flowing through it. Since there is a large difference between dielectric constant of oil and water, even small quantities of water can be detected in the oil outlet.

[50] Flow indicator is used by engine room personnel to check flow value. It is mechanical device that is not connected to control unit, but if the human operator takes action based on the instrument reading, then the indicator can be considered as a part of control loop with human operator taking function of control unit and actuator.

[51] Belongs to second category if conditions explained in (48) are met.

In principle main components of every separator have the same function but can differ in design and system layout. Samgong Mitsubishi separator has a integrated detection system called "Multi-Monitor" and its block diagram is shown on following figure.
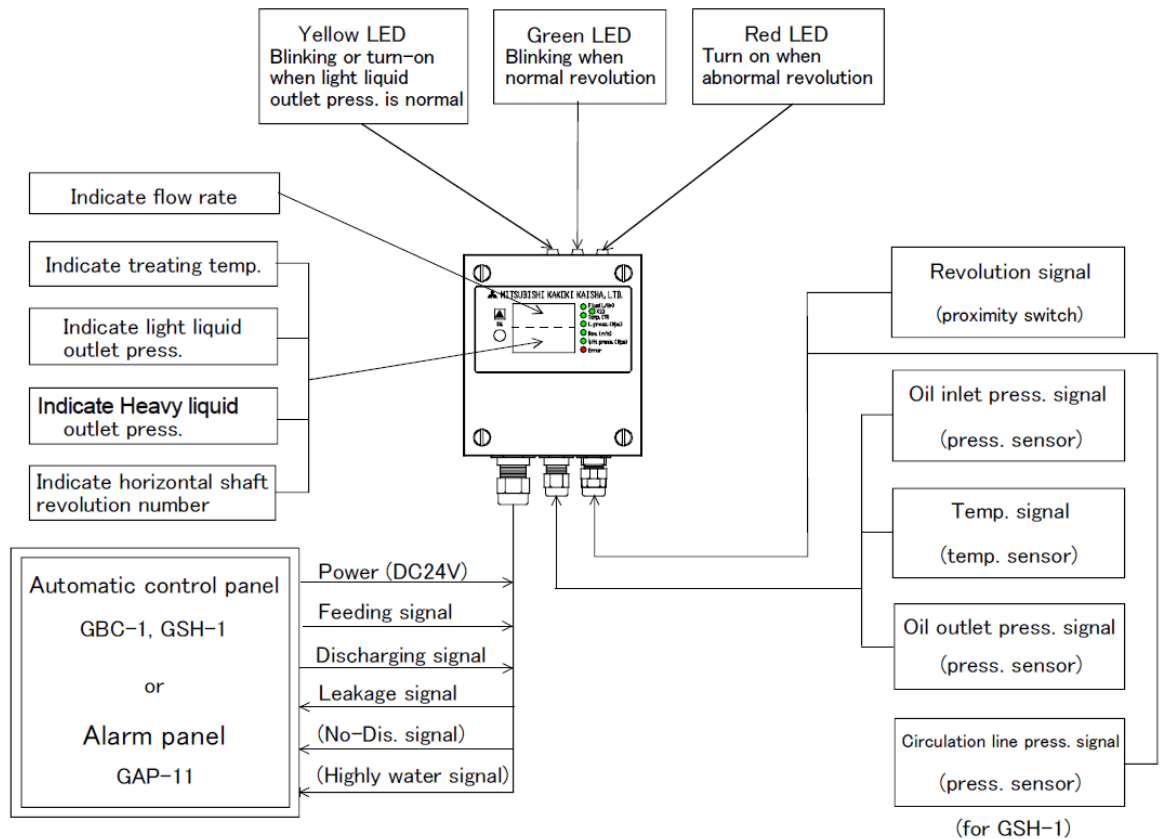


*Figure 54. Block diagram of Multi Monitor integrated detection system*

Multi monitor forms an integrated detection system with various detectors and data displays.

> ➢ LED display functions (Flow rate, Temperature, Pressure, Revolution number)
> ➢ Leakage Monitor (LM)
> ➢ Discharge Detector function (DD)
> ➢ Water Detector function (WD)

The Leakage Monitor Function (LM) of the Multi-Monitor is a protective device that detects leakage of treated oil to feed liquid outlet and leakage of treated oil from bowl's sludge outlet because bowl is not properly closed attributable to any reason.

Pressure sensor installed on the light liquid outlet connection piping of SELFJECTOR monitors the pressure at all times and if, for any reason, the pressure has dropped when the flow has decreased from a normal rate, deems treated oil is out-flowed and outputs an error signal.

Use of a precision pressure sensor allows to detect a large leakage flowing to the heavy liquid side as well as a slight leakage due to poor bowl opening. In the normal running condition, pressure control valve is arranged on the treated oil outlet piping is adjusted so as to apply certain pressure. If, on the account of accidental leakage of purifier, the pressure has dropped below an alarm trigger or lower limit level, an alarm is outputted.

Discharge detector function (DD) is a protective device that monitors sludge discharge and sends an alarm signal to the automatic control panel when it detects an abnormal discharge. The detection relies on the rotation speed change of the horizontal shaft to do the action meaning that if the rotation speed falls to a preset value due to sudden loss of energy by sludge discharge, it is detected by means of a proximity switch installed on the horizontal shaft to determine that sludge discharge has taken place.

Water detection function (WD) is used for Samgong Mitsubishi G-Hiddens series where separator works as a purifier and clarifier. Its function is to prevent separated water from leaking into light liquid (purified oil). Pressure sensor installed in the circulation line[52] allows for constant monitoring of separated water that is accumulated in the bowl. In the moment when separated water reaches the top disc outside level, the circulation of light liquid is stopped which causes an instantaneous drop in circulation line pressure. Pressure sensor will register such an event and the control unit will issue partial[53] or full discharge depending on the frequency of the previous partial discharges. [61]

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[52] Circulation line takes allows for a portion of a bowl content to be fed again back to the bowl via inlet (feed) line

[53] Partial discharge refers to the discharge of water through the water drain and full discharge to the complete bowl discharge of both sludge and water.

### 4.5.5. Actuators

Referring to the figure 51 where closed control loop block-diagram is shown all the devices which in physical manner whether mechanically, electrically, pneumatically, or hydraulically influence the separation process, fall into the category of actuators. So far electric motor starter, hydraulic mechanism for sludge discharge and its distributor – solenoid water block valve have been described.

Changeover three-way valve feeds dirty oil to the separator bowl or in case of separator trip, recirculates it back to the settling tank. The air used for control is received from solenoid valve block shown on following figure:
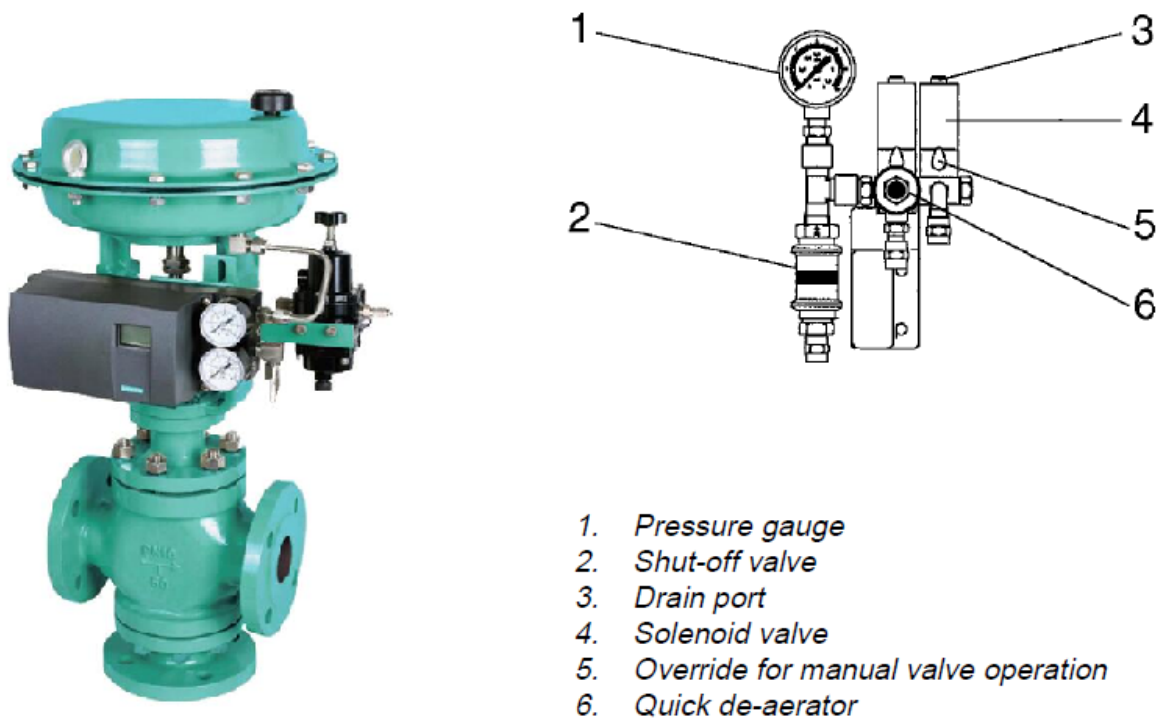


1. Pressure gauge
2. Shut-off valve
3. Drain port
4. Solenoid valve
5. Override for manual valve operation
6. Quick de-aerator

*Figure 55. Pneumatically controlled three-way valve (left),solenoid block valve, air (right)*

Working principle of valve block is following. Compressed air comes in to the valve block at the shut-off valve (2). The air pressure is indicated on the pressure gauge (1). The valve block comprises one or two solenoid valves (4), depending on the application. When the voltage goes off, the valve closes. The quick de-aerator (6) ensures a fast evacuation of air from the pneumatically operated valve, when the solenoid valve closes. [62]

The valve is equipped with a lever for automatic or manual operation. When the lever is turned to horizontal position, the valve is operated automatically, i.e. it is normally closed and opens when the solenoid is energized. When the solenoid is non energized, the valve can be opened manually by turning the lever to the vertical position.

## 4.6. SEPARATOR STARTING AND STOPPING

Starting of separator regardless of the manufacturer can be done in two ways namely, manually, or automatic. Manual starting requires knowledge about separation process and correct sequence of actions that are necessary for proper separator operation. It is used in events where automatic start is for some reason not possible. Automatic start is executed by control unit and requires minimum intervention from engine room officer. For the purposes of describing separator starting and stopping Kongsberg Norcontrol MC90 simulator is used where L.O. separator is started and stopped in both manners.

### 4.6.1. Setting the separation time

Proper separation time setting is important factor when considering quality of the product. When using time-dependent automatic control programs, accurate setting of the separation time (time between ejection cycles) is only possible if the throughput capacity and solids loading in the feed remain constant. If this is not the case, it may be necessary to correct the settings during operation.

The separating time depends on:

- the preselected operating mode (partial or total ejection),
- the solids loading in the feed,
- the consistency of the solids,
- the effective solids space volume in the bowl,
- the separator throughput

Given constant conditions the separating time can be determined by calculation or with the aid of the diagram. From practice following time periods have been proved (shown on next page)

| Product | Total ejection | Partial ejection |
|---|---|---|
| HFO | 2 h to max. 4h | 1h |
| MDO | 6h | 3h |
| LO mild | 6 to max. 8h | 3h |
| LO heavy duty | 2h to max. 4h | 1h |

*Table 4. Ejection times for lubricating and fuel oils*

Here is the example of mathematical calculation:

| | | |
|---|---|---|
| Given: | Solids content | p = 0.05% |
| | Solids holding volume space | V = 1.5 l |
| | Solids holding space given 75% utilization | V' = 1.13 l |
| | Throughput capacity | V° = 2000 l/h |
| Wanted | Separating time | t = ? |

The separating time to be set is calculated by following equation:

$$t = \frac{V'}{V° \cdot p} \cdot 60 \cdot 100 = \frac{1.13}{2000 \cdot 0.5} \cdot 6000 = 67.8 \min \approx 1.1 \, h$$

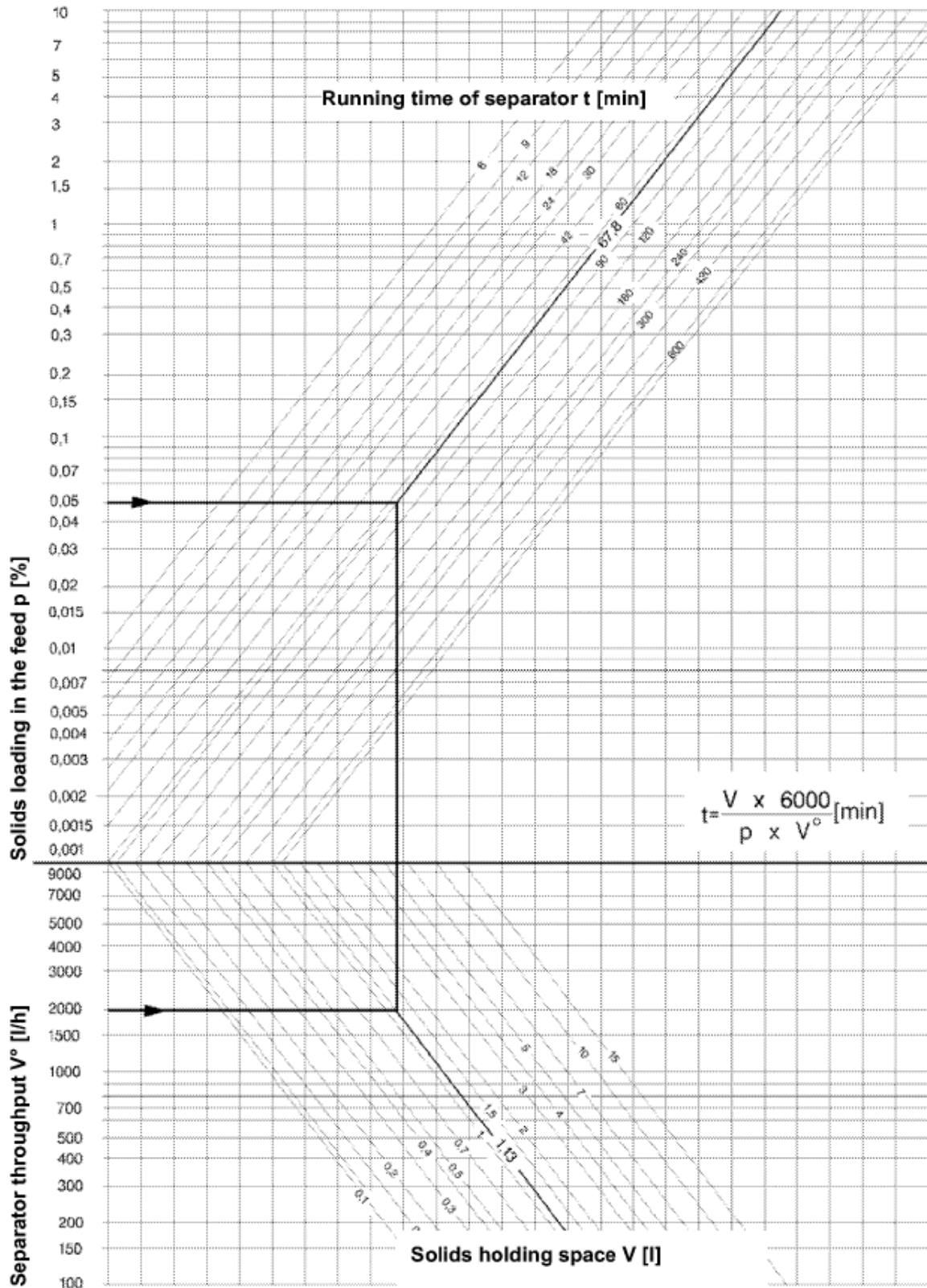The diagram that is used to calculate separation time graphically is shown on following page.

*Figure 56. Diagram for separation time calculation [63]*

### 4.6.2. Before start-up

After the separator had gone through maintenance or repair task it is necessary to take special caution before and after starting process begins. This involves checking the bowl height, making sure that it can rotate by hand. The symbol "O" must be aligned on the bowl bottom (or top) and on lock ring.

Before every start-up following points must be checked:

- ❖ the machine is correctly assembled,
- ❖ the hoses and hose pipes are undamaged and connected,
- ❖ the sight glass in the frame for observing belt/gear drive is clean,
- ❖ the gear chamber is filled with oil,
- ❖ the brake is released by turning handle clockwise,
- ❖ the hex head screws on the hood are tight,
- ❖ the handle connection piece is tightly bolted to the centripetal pump,
- ❖ the feed and discharge lines are connected and checked for signs of damage,
- ❖ the supervisory equipment is operational and the correct limit values are adjusted.
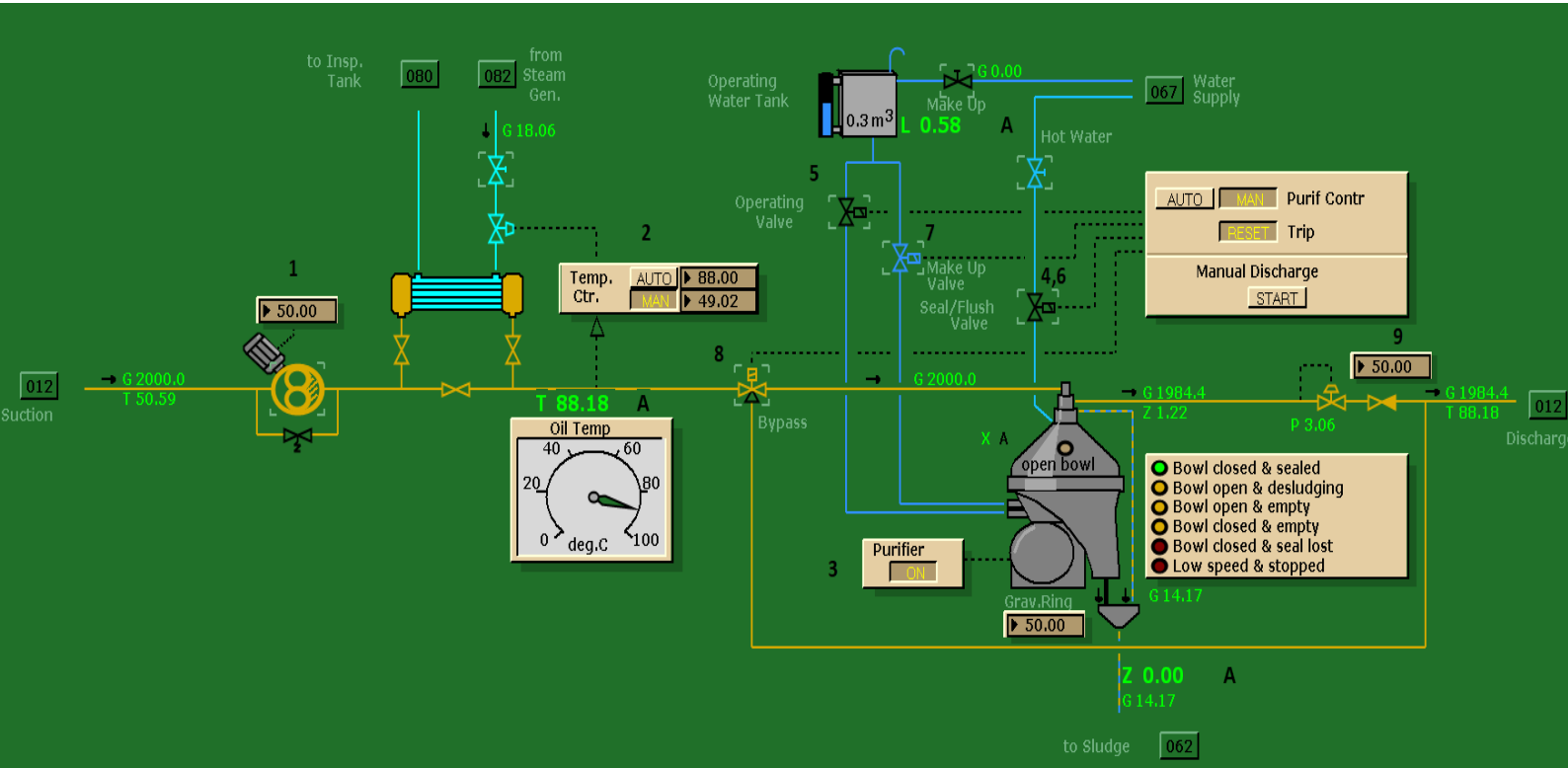
### 4.6.3. Manual start



*Figure 57. Procedure for manual L.O. separator start [28]*

Manual start carried out in situations when separator operation is necessary but automatic start is not possible. It is also useful to start separator manually so that the person is familiarized with locations of the valves and other ancillary separator equipment.

1. Check the position of the bypass valve and start the supply pump. Set the flow at around 50 % and check the pressure.

2. By adjusting position of the heater inlet valve ensure that the oil temperature is appropriate for separation.

3. Check the brake. Start the separator. Once the amperemeter value has stabilized the separator has reached its nominal revolution number.

4. Open Seal/Flush valve to wash the separator bowl.

5. Once the bowl is washed, open the operating valve so that water is fed to hydraulic mechanism thereby closing the bowl.

6. Now the bowl is ready to receive water seal through seal/flush valve.

7. Make up valve is kept opened so as to keep operating water pressure in necessary level.

8. Separator is filled with dirty oil by changing the position of bypass valve.

9. After all the parameters are checked, backpressure is set by adjusting the spring of the backpressure valve.

### 4.6.4. Automatic start

Majority of the starting process is done by control unit which operates solenoid valve, starters and automatically controls oil temperature.

1. Open the shut-off valve in the product feed line.

2. Switch on the motor. Compare the current and starting time with the diagram provided in instruction manual until the bowl reaches the speed specified on the separator nameplate.

3. Start preheater after motor is switched on.

4. Open the stop valve in the product discharge.

5. Switch on the control unit.

6. Start the program.

7. After the feed valves have automatically opened: set the backpressure in the product discharge to approx. 1.5 bar, adjust the desired throughput, when necessary, correct the backpressure in product discharge line.

8. Check the discharges for solids and dirty water; there must be no oil flow.

### 4.6.5. Manual and automatic stop

The difference between the two will be in a way bowl ejection command is issued (manually or automatically). However, even in case of automatic stop, following actions must be manually done.

1. Switch of the preheater. Product should be left flowing for a few more minutes since the preheater continues to heat for a short time.
2. Close the light liquid discharge.
3. Close the feed for operating water, filling, and displacement water.
4. Switch off the motor.
5. Switch off the feed pump.
6. Close the stop valve in the suction side of the feed pump (if installed) [63]

# 5. ADVANCED SEPARATION TECHNOLOGIES

In a more recent years marine industry has faced major changes. Due to new environment protection policies sulfur emissions have been reduced, with latest regulation enforced in January 2020. The global fleet is now confronted with a variety of new fuels because sulfur content has been slashed from 3.5% to 0.5%. Reducing sulfur content means changing the way in which fuels are now produced resulting in a wider range of fuel handling parameters then ever before. As described in chapter 3, the fluctuations in density and viscosity have a great impact on the efficiency of removing water and catalytic fines. In order to meet new standards and enhance separation process, new technologies are being implemented as a standard part of fuel system.

## 5.1. ALCAP WORKING PRINCIPLE AND CONSTRUCTION

ALCAP is a new model of separator manufactured by Alfa Laval and it stand for "Alfa Laval Clarifier and Purifier". As the name suggests this separator performs functions of clarifier and purifier i.e. removes water and dirt/cat particles at the same time. Because of diversity of fuels that are available in today's market, changing gravity disc would be necessary every time new type of fuel is bunkered. With ALCAP technology there is no need for gravity disc because these separators have the automatic function to adjust the oil/water interface based on the water content in the clean oil outlet, providing interruption-free operation.

The bowl of ALCAP separator is optimized to provide additional disc area, which leads to greater separation efficiency. To reduce energy consumption, a unique paring tube is fitted so that water can be removed from the bowl. Detection of water droplets in the clean oil outlet is achieved by means of water transducer that ensures automatic water drain (partial discharge) from separator as needed.

ALCAP technology monitors and removes both the water and the sludge that builds up inside the separator bowl. High water content in the fuel will trigger a water drain and sludge build-up will trigger the water transducer more quickly. When the water drainage occurs too frequently, the separator discharge is triggered (full discharge).

Fundamental feature of ALCAP separator is that its performance is not affected by fuel density and viscosity changes. Comparing to standard separators it can separate oils up to density of 1.05 kg/dm$^3$ (at 15°C) [65] because of its automatic adjusting function, there is no impact on the interface, nor can a loss of the water seal occur.
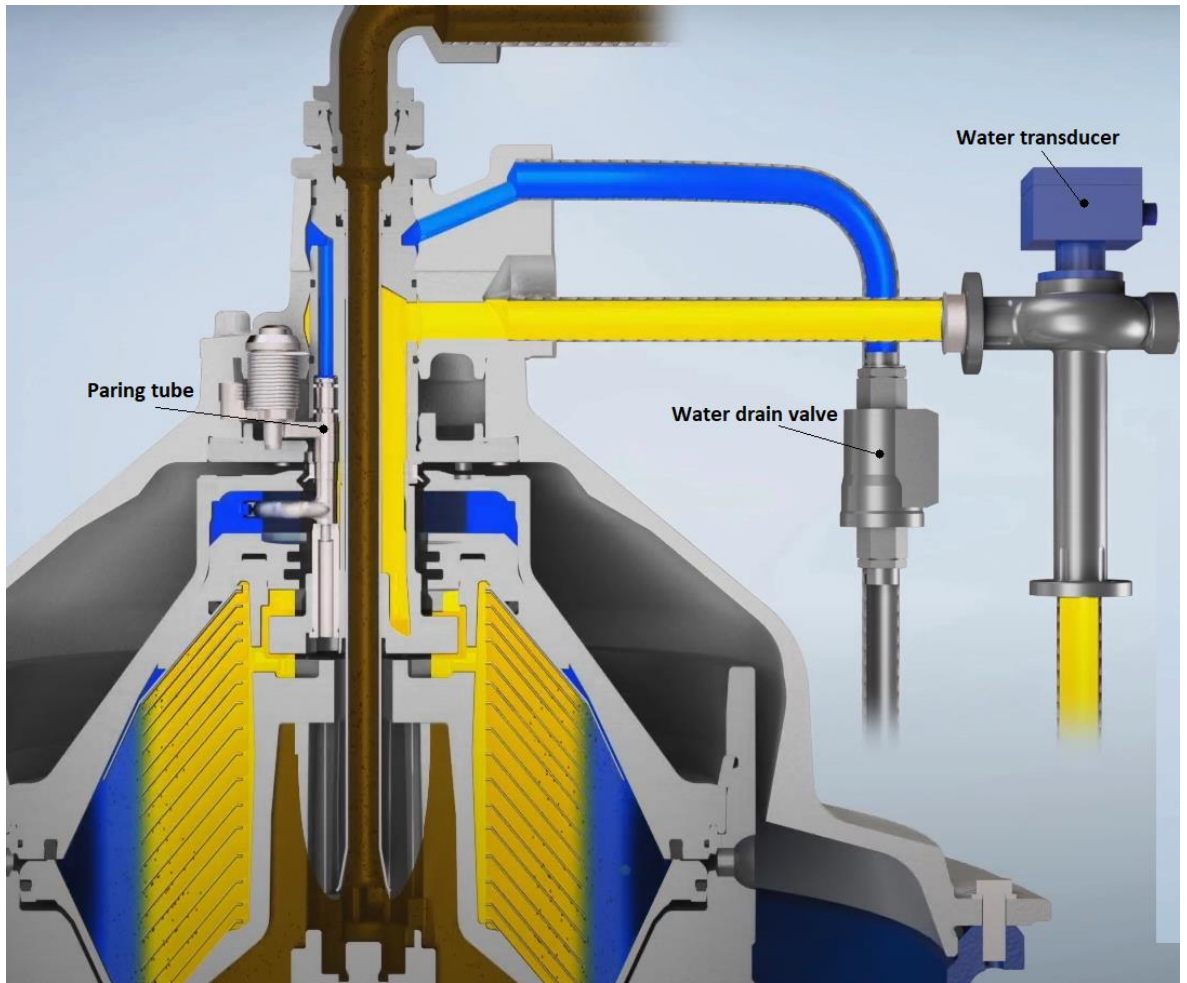
*Figure 58. Cross section of ALCAP [64]*

Besides the major one, there are several more features and benefits that are incorporated in Alfa Laval flex systems such as:

➢ *High flexibility* – separator size and the modular arrangement of the rest of equipment allows for easy installation and positioning in the engine room.

➢ *CentriShoot* – discharge system where instead of sliding bowl bottom system features a fixed discharge slide that flexes at its edge. This increases discharge accuracy and does away with metal-to-metal wear.

➢ *CentriLock* – conventional lock rings are threaded and must be removed with a sledgehammer. Over time, metal-to-metal wear between bowl and lock ring can lead to expensive bowl repair or replacement. Instead of conventional lock ring, the CentriLock bowl-locking system features a non-threaded snap ring that quickly snaps into place and is easily removed with only an Allen key.

➢ *Long service intervals* – Wear preventing features like CentriShoot and CentriLock reduce consumption of spare parts and allow planned maintenance to be performed less often which in turn reduces operating costs.

## 5.2 G-HIDDENS AUTOMATIC OPERATION

G-Hiddens is manufactures by Mitsubishi Samgong and belongs to the same class of separators as ALCAP and Gea Wesphalia UNITROL. Comparing to latter two G-Hiddens is different in multiple ways[54] but they share key features such as: ability to separate oils of densities up to 1.01 kg/dm$^3$ and partial discharge function to periodically drain only accumulated water. In this chapter automatic operation of the G-Hiddens separator will be presented.

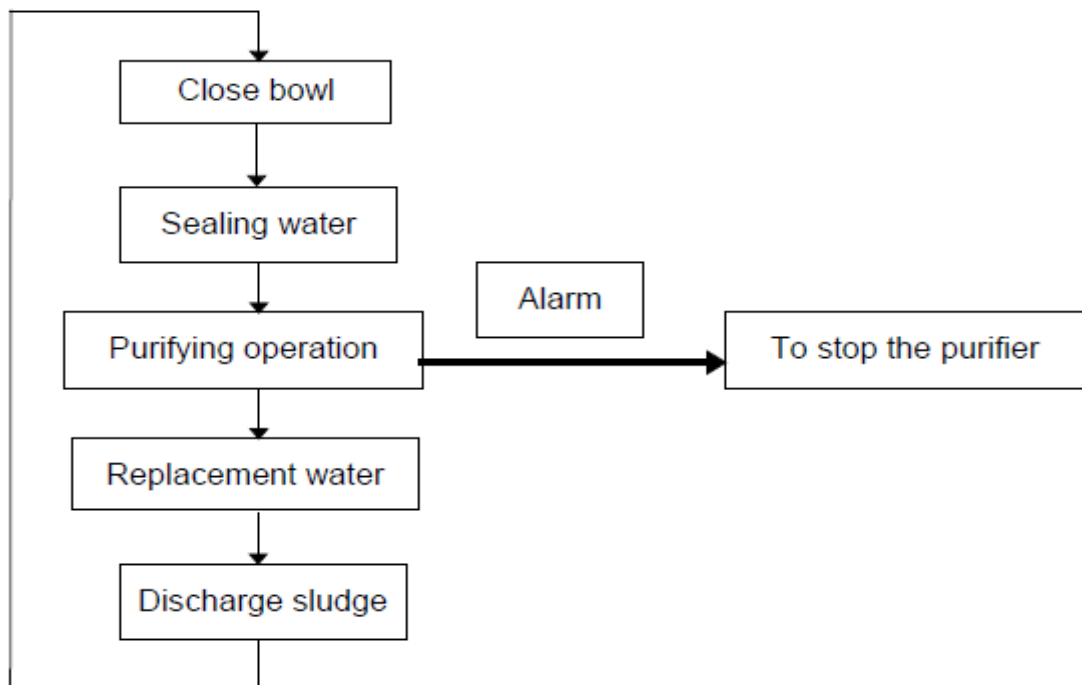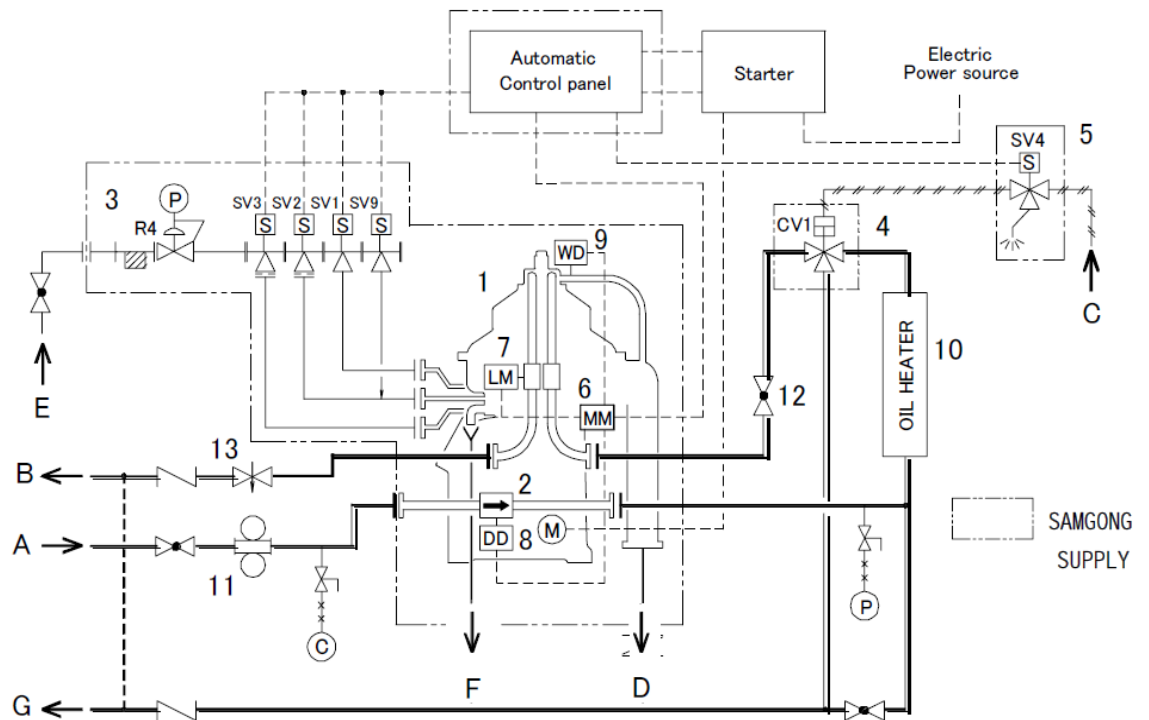Every separator follows the loop shown below:



*Figure 59. Separator operation program [67]*

Separator and its equipment are graphically laid-out in flow chart figures. These allow for detailed description of the automatic process since every element involved in the process is shown in physical connection to every other.

---

[54] The difference is in for example: sludge discharge mechanism, detection of water accumulation in the bowl and has a gravity ring, but of constant diameter for range of all oil specific gravities.

| 1 | SELFJECTOR | A | Dirty oil inlet |
|---|---|---|---|
| 2 | Gear pump | B | Purified oil outlet |
| 3 | Solenoid valve unit for operating water<br>　　SV1 : Solenoid valve (for Bowl opening water)<br>　　SV2 : Solenoid valve (for Bowl closing water)<br>　　SV3 : Solenoid valve (for Sealing water)<br>　　SV9 : Solenoid valve (for Partial bowl opening water) | C | Compressed air inlet |
| 4 | 3-way cylinder valve (Feed valve) | D | Sludge & water outlet |
| 5 | 3-way solenoid valve (SV4 : for feed valve air supply) | E | Water inlet |
| 6 | Air filter (for feed valve) | F | Drain |
| 7 | Multi-monitor | G | Circulation |
| 8 | Leakage Monitor Function(LM) | ⓟ | Pressure gauge |
| 9 | Discharge Detector Function(DD) | ⓒ | Compound gauge |
| 10 | Water Detector Function(WD) | ⓜ | Motor |
| 11 | Oil heater | | |
| 12 | Oil Strainer | | |
| 13 | Flow control valve | | |
| 14 | Pressure control valve | | |

*Figure 60. Samgong Mitsubishi G-Hiddens automatic operation flow chart [68]*

Separator is started via separately installed starter. On the control panel power switch is set to "ON". Since the control unit is now operational, timers and counters can be set via buttons and display. In order to confirm that the separator has reached its rated speed, amperemeter is checked. Thereafter, by pressing "AUTO START" provided on the control panel, automatic operation begins.

In following are steps in which timers of separator controller in the automatic control panel work to perform continuous operation.[55]

1. The interval timer T000 beings working. Solenoid valve SV2 will open to supply the bowl closing water and close the bowl.

2. When T000 is timed up, solenoid valve SV2 will close to stop supplying the bowl closing water. Solenoid valve SV3 will open to supply the replacement water. Replacement timer T002 will start operation.

3. When T002 is timed up, solenoid valve SV3 will close to stop supplying replacement water. Solenoid valve SV1 will open to supply the bowl opening water and open the bowl. Bowl opening water timer T001 will start operation.

4. When T001 is timed up, solenoid valve SV1 will close to stop supplying the bowl opening water. Solenoid valve SV2 will open to supply the bowl closing water and close the bowl. At the same time, the interval timer T000 will start operation.

5. When T000 is timed up, solenoid valve SV3 will open to supply the regulating water. Regulating water timer T003 will start operation. At the same time, interval timer T000 will restart operation.

6. When T003 is timed up, solenoid valve SV3 will close to stop supplying regulating (replacement) water

7. When T000 is timed up, solenoid valve SV4 will open to supply operating air and open the feed valve to supply the feed oil into the bowl and start separation. At the same time, discharge interval timer C015 will restart operation. During operation of the discharge interval timer C015, the bowl closing water will be intermittently supplied. In other words, the following processes will be repeated: Operation C014 → Expiry of C014 → Operation of T016 (open SV2 to supply the bowl closing water) →Expiry of T016 (closes SV2 to stop supplying the bowl closing water) → Operation of C014. Besides latter, the feeding signal will be output to the Multi-Monitor. In case that Monitoring timer C022 has not expired, automatic control executes and continues operation from step 20.

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[55] For functions of each timer and counter refer to table on page 84.

8. When a water detection signal is received from Multi-Monitor (When the Monitoring timer C022 has expired), or when C015 timer expires following events will take place. Discharge interval timer C015 will be reset. Monitoring timer C022 will be reset. Solenoid valve SV4 will turn off to close the feed valve. At the same time, interval timer T000 will start operation. The "Feeding" signal output to the Multi-Monitor will be stopped. The "Discharge process" signal will be output to the Multi-Monitor.

9. When T000 is timed up, solenoid valve SV3 will close to stop supplying the replacement water. Replacement water timer T002 will start operation. The bowl washing counter C023 is counter one time and is added one time to the current count.

10. When T002 is timed up, solenoid valve SV3 will close to stop supplying replacement water. Immediately, solenoid valve SV1 will open to supply opening water and open the bowl for sludge discharge. Bowl opening water timer T001 will start operation.

11. When T001 is timed up, solenoid valve SV1 will close to stop supplying the bowl opening water. Solenoid valve SV2 will open to supply the bowl closing water and close the bowl. At the same time, interval time T000 will start operation. In case that bowl washing counter has not expired, automatic control executes step 19.

12. When T000 is timed up (and the bowl washing counter C023 has expired), interval timer T000 will restart operation. Output of the "Discharge process" signal to the Multi-Monitor is stopped.

13. When T000 is timed up, solenoid valve SV3 will open to supply the bowl washing water. Solenoid valve SV2 will close to stop supplying the bowl closing water. Bowl washing water timer T004 begins operating.

14. When T004 is timed up, solenoid valve SV3 will close to stop supplying the bowl washing water. At the same time, solenoid valve SV1 will open to supply the bowl opening water and open the bowl to discharge washing water. Bowl opening timer T001 will start operation.

15. When T001 is timed up, solenoid valve SV1 will close to stop supplying the bowl opening water. Solenoid valve SV2 will open to supply the bowl closing water and close the bowl. Immediately water timer T001 will start.

16. When T000 is timed up, solenoid valve SV3 will open to supply the regulating water. Regulating water timer T003 will start operation. Interval timer T000 will restart operation.

17. When T003 is timed up, solenoid valve SV3 will close to stop supplying the regulating water.

18. When T000 is timed up, solenoid valve SV2 will close to stop supplying the closing water. Interval timer T000 will restart operation. After step 18, separator operation procedure returns to step 7.

19. When T000 is timed up (When the bowl washing counter has not expired), solenoid valve SV3 will open to supply the regulating water. Regulating water timer T003 will start operation. The "Discharge process" signal output to the Multi-Monitor will be stopped. Interval timer T000 will restart operation. Automatic control returns to execute step 17.

20. When a water detection signal is received from the Multi-Monitor (When the Monitoring timer C022 has not expired), operation of discharge interval timer C015 will be stopped temporarily (Lapsed time is held). Monitoring timer C022 will be reset. Solenoid valve SV4 will close to close the feed valve. Solenoid valve SV2 will stay open to supply bowl closing water. Interval timer T000 will restart operation. The "Feeding" signal output to the Multi-Monitor will be stopped. The "Discharging" signal will be output to the Multi-Monitor.

21. When T000 is timed up, solenoid valve SV3 will open to supply replacement water and the replacement water timer T012 will start operation.

22. When T012 is timed up, solenoid valve SV3 will close to stop supplying the replacement water. Solenoid valve SV2 will stay open to supply bowl closing water and close the bowl. Interval timer T000 will start operation.

23. When T000 is timed up, solenoid valve SV9 will open to supply bowl opening water for partial discharge to the bowl so that sludge and separated water are discharged. Opening bowl timer T011 will start operation.

24. When T011 is timed up, solenoid valve SV9 will close to stop supplying the bowl closing water. Solenoid valve SV3 will open to supply regulating water. Regulating water timer T013 will start operation. Interval timer T000 will start operation.

25. When T013 is timed up, solenoid valve SV3 will close to stop supplying regulating water.

26. When T000 is timed up, solenoid valve SV2 will close to stop supplying the bowl closing water. The "Discharging" signal output to the Multi-Monitor will be stopped. Interval timer T000 will restart operation.

27. When T000 is timed up, operation of discharge interval timer C015 will be re-started. Monitoring timer C022 will start operation. During operation of discharge interval timer C015, the bowl closing water will be intermittently supplied. In other words, the following process will be repeated: Operation of C014 → Expiry of C014 → Operation of T016 (opens SV2 to supply bowl closing water) → Expiry of T016 (closes SV2 to stop supplying bowl closing water) → Operation of C014. Lastly, the "Feeding" signal will be output to the Multi-Monitor.

After step 27 has been executed, automatic control program returns to step 7. [68]

# 6. SEPARATOR ALARMS AND TROUBLESHOOTING

Important element of every automated system that is supervised by human personnel is alarm system. Its function is to inform about changes in process parameters by means of visual and audible signals. In the context of ships engine room, they allow for non-supervision during night hours, because information about the state of alarm system can be obtained from the alarm panel located in the room of engine officer.

During system/process design and test run, optimal parameter boundaries are determined. While system is operating within those boundaries its performance is efficient and safe with long operation time between maintenance schedules. Therefore, every significant deviation from such conditions must be informed to the engine room crew.

Alarms are indicators that the fault has occurred which produced unwanted conditions in which system is then operating. The task of the crew is to immediately respond with appropriate actions to a such event. In this chapter lists of alarms, faults, and their remedies for ALCAP with possible causation will be presented.

## 6.1. CONTROL UNIT AUTOMATIC RESPONSE

When the alarm signal reaches the control unit, safety response will be executed as a precautionary measure. Its function is first and foremost ensuring safety to human personnel that can potentially be in close proximity to device and secondary, to minimise potential damage to the equipment so after the fault has been taken care of, the device can continue its normal operation.

Output from control unit is sent to actuator of three-way recirculation valve that directs changes the direction of dirty liquid flow so it is returned back to the settling tank[56]. Secondly the light liquid is displaced thereby saved from being ejected into sludge tank. The motor will keep running if there is no fault on the motor side.

Control unit issues the alarm which is first indication to the engine room crew about the part of separation system that is defective. Besides audio signal, information about the faulty state can be found on control unit display.

Depending on the type of fault, additional commands are executed, for example if the separation temperature is too high, then the heater will be turned off.

One fault can be a result of another fault. In that case finding the first fault (root cause) is necessary to fully resolve operation defect. Example of such event is liquid flowing through the bowl casing drain or sludge outlet which was produced by too low bowl speed.

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[56] In case of L.O. it is returned to the sump tank.

## 6.2. ALARMS AND FAULT FINDINGS

### 6.2.1. Alarms

High oil pressure – is an event that arises due to disturbances in the piping. Causes are due to downstream throttling or closure of regulating or backpressure valves. Corrective action is to open or adjust position of regulating valve, setting the pressure to the value listed in instruction book. After fault has been solved recirculation valve should be returned to normal position i.e., feed to the separator.

Low oil pressure – there are many possible reasons for such event. If the oil feed is too low, oil feed pump should be checked, and flow adjusted. Another possibility is clogged strainer which should be inspected. It could be the case that for some reason feed pump has stopped and should be started again with attention to see what went wrong in the first place. If the oil doesn't reach separator, recirculation valve should be examined more precisely air solenoid valve block that feeds control air to the valve. Remedy for low backpressure is adjustment of regulating valve position so that pressure increases to the value which is recommended by instruction manual. In case where bowl opened accidently during operation, bowl opening valve should be checked. Low oil pressure can also be sign of oil leakage, that is, light liquid flowing through sludge outlet or bowl casing drain.

Sludge discharge failure – this alarm is activated only after two attempts to discharge within the same discharge cycle have failed. Water supply system must be checked since the cause of failure can be very low of lack of opening water supply. Recommended values for water flow are different for each separator and are listed in instruction manual. Another cause can be damaged opening water valve and it should be checked. Also, if there is no signal from low oil pressure switch at discharge sludge discharge failure is possible. When dosing ring is tightened too much separator will not be able to perform sludge discharge which is another possible cause of a failure.

Water transducer fault – there are two classes of causes related to this fault. If the transducer circuit board and oscillator are loosely connected, then their connection must be inspected. Another class is faulty oscillator unit or faulty control unit module. To determine whether its one or the other, check the supply voltage in the MT4 on terminal 3-4. About every fifth second the voltage at terminal (20V DC) will drop for approximately 0.5 second. If there is voltage drop, replace oscillator unit. Otherwise replace control module.

Vibrations – alarm trigger is vibration switch that is activated once the separator bowl is out of balance. Vibration switch should be inspected. Separator is stopped and requires bowl inspection, cleaning and afterwards it can be restarted. More details about causes and remedies in chapter 6.2.2.

Heater Fault – oil flow has stopped, or temperature switch tripped. Cause for oil flow defect must be investigated as well as flow and temperature switch settings. If the heater is clogged, then it should be cleaned. If the safety switch tripped heater is automatically turned off

High or Low Oil Temperature – low temperature alarm will occur in case that: heater is clogged, there is no sufficient steam supply, steam trap or steam supply valve is faulty or there is electrical fault so that fuse has tripped. High temperature occurs when steam supply valve is does not operate correctly or is electrical control system out of action.

Temperature limits could incorrectly set i.e., too close to the set point value. When starting separator, it is necessary to wait for increase of oil temperature. If the temperature sensor (PT100) is faulty then it should be replaced.

Communication error – arise when there is fault in the information flow between circuit boards or with external computer. In first case fuses should be checked or control module replaced. In second case external and internal connections should be inspected and if there is internal communication error then the remedy is replacement of control module.

Processor fault – For "mode switch error" check correct position of mode selector. If there is error in analog/digital conversion first inspect the fuse A1:F2 located on front board and if correct, control module should be replaced. Error related to memory such as: internal RAM, external RAM, E2 RAM and program error all require module replacement.

Power failure – takes place as loss of electrical supply or when electrical frequency oscillates above allowed limit (+ 5%). First response is to check power supply. If the power has been off more than 10 minutes, the separator bowl must be stopped and manually cleaned before the start. Then the heater, separator and control program can be restarted.


ALCAP Alarms – High water transducer value is an indication of high water content in oil. Check the oil system for water leakage. The same alarm will occur if the water transducer is dirty so the contact surfaces should be inspected and cleaned if necessary. If the value is too low, then possible reasons are bad connections between oscillator unit and electrode or cable damage. In case of PROM and/or RAM faults, control module must be replaced.

Belonging to the same alarm code are following situations: water transducer trigger value is less than 30, insufficient displacement and conditioning water. Check the following components: valve block strainer is free from deposits, displacement water flow is correct, inner water pipe in the separator inlet pipe is free from deposits, seal ring and sealing surface on the sliding bowl bottom are free from any damage. If the problem still persists after one has checked all the previously mentioned components, then the parameter settings in control unit need adjustment.

Last ALCAP alarm is water transducer triggering 5 times in a row. Corrective actions are investigation of potential water leakage into lube oil system or changeover to stand-by mode. [69]

### 6.2.2. Faults

In this chapter causes and corrective actions for each fault will be presented in a table format.

#### 6.2.2.1. Mechanical functions

Separator vibration is normal during the starting and stopping sequences when the separator passes through its critical speeds. However, if the excessive vibration occurs, separator must be immediately stopped while keeping the bowl filled with liquid during rundown.

**Separator vibrates**

| Cause | Corrective actions |
|---|---|
| Bowl out of balance due to: poor cleaning, incorrect assembly, incorrect disc stack compression, bowl assembled with parts from other separators | Dismantle the separator and check the assembly and cleaning |
| Uneven sludge deposits in the sludge space | Dismantle and clean the separator bowl |
| Height adjustment of the oil parting disc or bowl spindle is incorrect | Stop the separator, measure and, if necessary, adjust the height(s) |
| Bowl spindle bent (max 0.04 mm) | Renew the bowl spindle |
| Bearing is damaged or worn | Renew all bearings |
| Vibration damping rubber cushions are worn out | Renew all rubber cushions |
| Spindle top bearing spring is broken | Renew all springs |

**Smell**

| Cause | Corrective actions |
| --- | --- |
| Normal occurrence during start while the friction blocks are slipping | None |
| Brake is applied | Release the brake |
| Oil level in gear housing too low | Check oil level and add oil if necessary |

**Noise**

| Cause | Corrective actions |
| --- | --- |
| Oil level in gear housing is too low | Check oil level and add oil if necessary |
| Height adjustment of the oil paring disc or bowl spindle is incorrect | Stop the separator, measure, and adjust the height(s) |
| Worm wheel and worm are worn | Renew worm wheel and worm |
| Bearing is damaged or worn | Renew all bearings |
| Incorrect play between coupling pulley and elastic plate | Adjust the play |

**Speed too low**

| Cause | Corrective actions |
| --- | --- |
| Brake is applied | Release the brake |
| Coupling pads are oily or worn | Clean or renew friction pads |
| Bowl is not closed or leaking | Dismantle and check the bowl |
| Motor failure | Repair the motor |
| Bearing is damaged | Renew all bearings |
| Incorrect gear transmission (60 Hz gear for 50 Hz power supply) | Stop and change the gear transmission to suit the power supply frequency |
| Incorrect coupling friction blocks (60 Hz blocks for 50 Hz power supply) | Change the friction blocks to suit the power supply frequency |

**Starting power too high**

| Cause | Corrective actions |
|---|---|
| Incorrect friction blocks (50 Hz blocks for 60 Hz power supply) | Stop immediately and change the friction blocks to suit the power supply frequency |
| Friction pads are oily or worn | Clean or renew friction pads |
| Motor failure | Repair the motor |

**Starting time too low**

| Cause | Corrective actions |
|---|---|
| Brake is applied | Release the brake |
| Friction pads are oily or worn | Renew or clean friction pads |
| Height position of oil paring disc or operating device is incorrect | Stop, check and adjust the height |
| Motor failure | Repair the motor |
| Bearing is damaged or worn | Renew all bearings |

**Water is worm gear housing**

| Cause | Corrective actions |
|---|---|
| Bowl casing drain is obstructed | Clean the casing and the drains properly. Solve the reason for obstruction. Clean worm gear housing and change oil. |
| Leakage at top bearing | Renew seal ring and change oil |
| Condensation | Clean worm gear housing and change oil |

*6.2.2.2. Separating functions*

**Liquid flows through the bowl casing drain and/or sludge outlet**

| Cause | Corrective action |
|---|---|
| Sludge discharge or water draining in progress | Normal operation, does not require any action |

| | |
|---|---|
| Strainer in operating water line is clogged or water pressure/flow too low | Clean the strainer and check water/pressure flow, closing water pressure 20-30 kPa |
| Channels in operating water device are clogged | Clean the operating water device |
| O-ring at the paring tube chamber cover (small lock ring) is defective | Renew O-ring |
| Paring chamber cover (small lock ring) is defective | Renew the paring chamber cover |
| Seal ring in oil paring disc device is defective | Renew the seal ring |
| Sealing edge of the sliding bowl bottom is defective | Smoothen sealing edge of the sliding bowl bottom or renew it |
| Valve plugs defective | Renew all valve plugs |

## Bowl opens accidentally during operation

| Cause | Corrective action |
|---|---|
| Strainer in the operating water supply is clogged | Clean the strainer |
| No water in the operating water system | Check the operating water system and make sure the valve(s) are open |
| Water connections to the separator are incorrectly fitted | Rectify |
| Upper nozzle in the dosing ring is clogged | Clean the nozzle. Carry out an Intermediate Service (IS) |
| Square-sectioned ring in the sliding bowl bottom is defective | Renew the square-sectioned ring. Carry out an Intermediate Service (IS) |
| Valve plugs are defective | Renew all plugs. Carry out an Intermediate Service (IS) |
| Supply valve for opening water is leaking | Rectify the leak |

**Bowl fails to open for sludge discharge**

| Cause | Corrective action |
|---|---|
| Strainer in the operating water supply is clogged | Clean the strainer |
| Seal rings in operating water device are defective | Renew the seal rings |
| Opening water flow is too low | Check the opening water flow (minimum 18 litres/minute) |
| Dosing ring is too firmly tightened | Check the tightening torque |
| Lower nozzle in the dosing ring is clogged | Clean the nozzle. Carry out an Intermediate Service (IS) |
| Seal ring in the operating slide is defective | Renew the seal ring. Carry out an Intermediate Service (IS) |

**Unsatisfactory sludge discharge**

| Cause | Corrective action |
|---|---|
| Dosing ring is too firmly tightened | Check the tightening torque |
| Valve plugs in the operating slide are too high | Renew with correct valve plugs |
| Sludge deposits in the operating system | Check and clean the operating system |

**Unsatisfactory separation**

| Cause | Corrective action |
|---|---|
| Incorrect separation temperature | Check temperature controller or adjust manually |
| Throughput is too high | Adjust flow control valve |
| Disc stack is clogged | Clean disc stack |
| Sludge space in bowl is filled | Clean and reduce the time between sludge discharges |
| Bowl speed is too low | Examine the motor and power transmission including the gear ratio |

**High pressure in oil outlet**

| Cause | Corrective actions |
|-------|--------------------|
| Throughput is too high | Adjust flow control valve |
| Valve(s) in the oil outlet line is closed | Open the valve(s) |
| Bowl disc stack is clogged | Clean disc stack |

*6.2.2.3. Vibration switch*

**Vibration switch does not reset**

| Cause | Corrective actions |
|-------|--------------------|
| Dirt or iron particles on magnets | Clean magnets |
| Leaf spring is broken | Return to Alfa Laval for repair |
| Reset coil is open | Check for continuity and proper coil resistance |

**Impossible to adjust setpoint to obtain tripping**

| Cause | Corrective actions |
|-------|--------------------|
| Incorrect air gap between hold-down magnet (lower) and armature in switch | Readjust the air gap with the stop pin screw |

**Vibration switch does not reset**

| Cause | Corrective action |
|-------|-------------------|
| Defective switch | Renew and verify by manually moving the armature to the latched (tripped) position and listen for an audible click. Verify contact by performing a continuity check |

| Incorrect position | Check that the switch plunger is just free of the armature when in the set (un-tripped) position |
|---|---|

## 6.3. ENGINE OFFICER APROACHES AND PRINCIPLES

At the moment when engine officer hears the alarm, he immediately responds. The longer it takes to take action in response to the fault, the more severe damage can take place. The simplest and most effective action to prevent potential hazard is to stop device operation. When the filling of the fuel daily tank is stopped, it still has sufficient quantity to serve main engine (and the rest of consumers) for at least couple of hours. If preliminary inspection of the separator shows that it requires longer downtime to diagnose and correct the fault, then second separator can be put into operation.

When it comes to fault diagnosis, simple but effective principle is to start causes that are most likely to happen or ones that are easily checked. For example, if the separator throughput is low, it is more convenient to first check the filter or pump, then it is to dismantle separator bowl and look for deposits build up or similar. It is sometimes case that the cause of fault can be found relatively easy.

However, it is not often the case. Instruction books offer general guidelines about potential causes and actions to restore device normal operation, but often engine officers report faults that occurred where instruction book troubleshooting section offered little no aid at all.

When faults and corrective actions occur on a device, they are recorded in a book or log that is kept by officers who are in charge of device operation. For separators it is 4th engineer. It is useful to have historic record about faults, overhauls and similar data, for it is often the case that the same faults repeat.

Beside checking such data source, conversation with a colleague can be of great aid. Maybe he was on board ship when the same fault occurred and can, based on previous experience, make a decent if not 100% correct estimation about fault origin.

Locus of fault diagnosis is a person that is, a member of the engine room. There are several factors that decrease effectiveness or ability of a person to perform such task, and first step helpful step is to be aware of them. Psycho-physical state reflected in mood or fatigue can significantly influence the performance of a person performing the task of fault diagnosis. If one is nervous or tired, a little pause can refresh the mind and therefore increase performance and results.

Other factors that can influence the outcome of fault diagnosis are (relating to device): lack of detailed schemes, complexity and price, inexperience, fear from dismantling if there are no spare parts, pressure exerted by company policies and limited amount of time available for fault diagnosis. [71]

# 7. CONCLUSION

In this thesis process of diagnosing faults on centrifugal separator was structured in a way to present all its related aspects. It starts with ability of fault detection that is, once the fault occurs it cannot be diagnosed, before it is detected. Control unit constantly monitors separator operation parameters whose deviation is indicator that something is wrong.

When interviewing colleagues about their fault diagnosing experience, they were employing neither classification nor inference methods strictly, but relied more on their intuition which is a result of theoretical knowledge and experience of working in engine room complex. Nevertheless, there is a pattern between diagnosis methods that can be learned from theoretical books, and ones that come naturally through practice in working environment.

Big emphasis in thesis was on understanding separator principle operation and all the sub-system that comprise it. Theoretical knowledge presents solid foundation upon which engineering intuition about fault diagnosis can be build on. Learning about fault diagnosis methods through literature and employing it later in practise significantly increases competence and performance of engine room officer.

The key principle for handling faults can be found in the Latin proverb *"Praestat cautela quam medela"* which points out to the fact that preventing a fault is much better option then diagnosing and correcting it. For that reason regular maintenance schedules and instructions provided by separator manufacturer should be respected and followed.

Fault diagnosis is a complex process that requires several steps for successful completion. Besides being familiar with methods and techniques that were developed in the scientific field of fault diagnosis, having theoretical and practical knowledge about the device, its operating sequences and sub-components is essential for the duty carried out by engine room officers.

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# LIST OF ABBREVIATIONS

HFO – Heavy Fuel Oil

LO – Lubricating Oil

MDO – Marine Diesel Oil

RAM – Random Access Memory

ROM – Read Only Memory

EEPROM – Electrically Erasable Programmable Read Only Memory

PLC – Programmable Logical Computer

PID – Proportional Integrational Derivative

T – Timer

C – Counter

LM – Leakage Monitor

DD – Discharge Detection

WD – Water Detection

ALCAP – Alfa Laval Clarifier and Purifier

# LIST OF TABLES
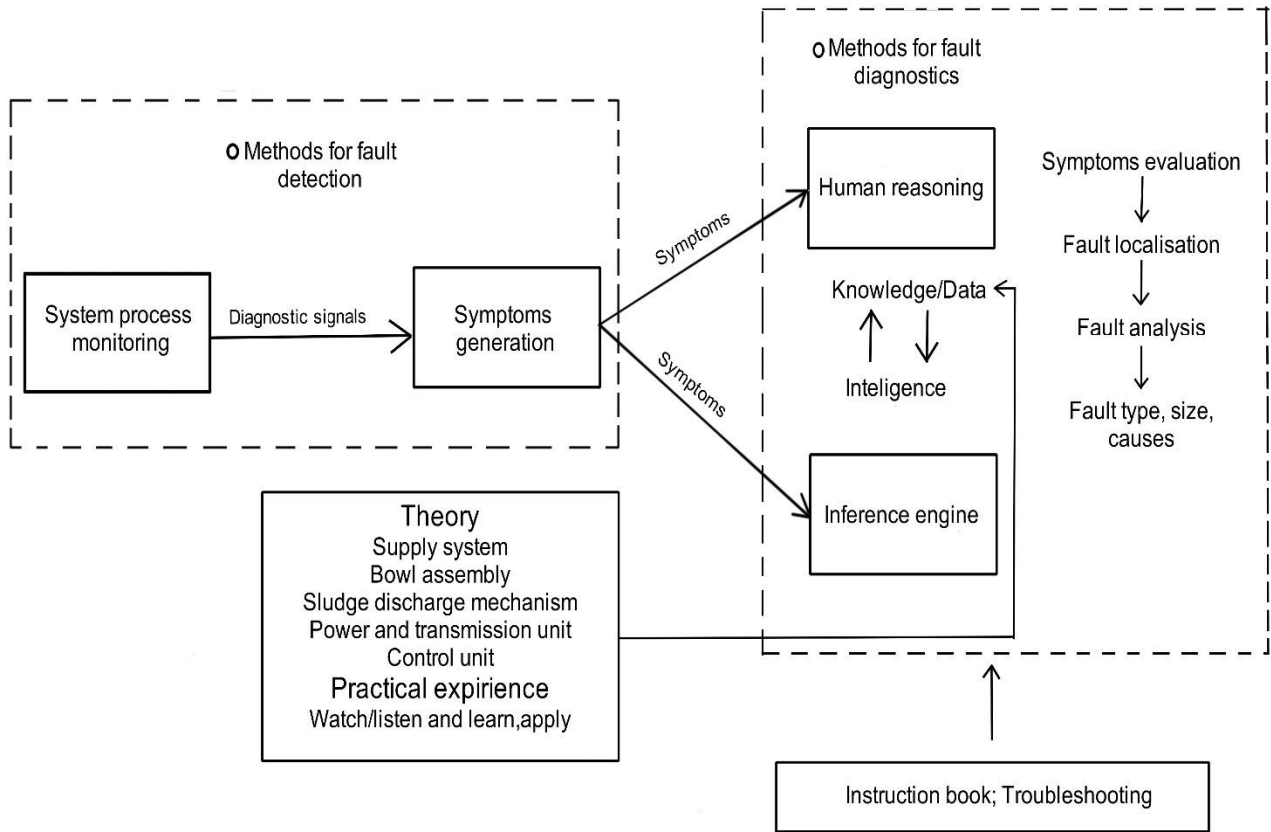
# LIST OF FIGURES

## ACCESSORIES



Simulation #1 Effect of flow control on clean oil outlet quality



Simulation #2 – Effect of flow control on clean oil outlet quality

Master thesis blueprint